The Streamwise Turbulence Intensity – A Comparison between Smooth and Rough Wall Turbulent Boundary Layers

A. Segalini, R. Örlü, Ian P. Castro, and P. Henrik Alfredsson

Abstract. Clear differences in turbulence intensity profiles in smooth, transitional and fully rough zero-pressure gradient boundary layers are demonstrated, using the diagnostic plot (u'/U vs. U/U_∞ where u' and U are the local fluctuating and mean velocities and U_∞ is the free-stream velocity). A wide range of published data is considered and all zero-pressure gradient boundary layers yield outer flow u'/U values which are roughly linearly related to U/U_∞, just as for smooth walls, but with a significantly higher slope. The difference in slope is due largely to the influence of the roughness parameter (ΔU^+ in the usual notation) and all the data can be fitted empirically by using a modified form of the scaling, dependent only on $\Delta U^+/U_\infty^+$. It is observed that the turbulence intensity, at a location in the outer layer where U/U_∞ is fixed, rises monotonically with increasing $\Delta U^+/U_\infty^+$ regardless of the roughness morphology.

1 Introduction

The turbulent boundary layer over a rough wall is a canonical flow case that, despite its long history, is still a subject of numerous debates regarding the physical phenomena involved and its appropriate scaling. Compared to a turbulent boundary layer over a smooth wall with the same Reynolds number based on the thickness of the boundary layer, δ, and the friction velocity, u_*, the mean velocity over the rough wall is lower than the corresponding one measured at the same height over a smooth surface. This velocity difference is usually assumed to be constant from the roughness surface to a height $y = \delta$, and is referred to as the *roughness function*, ΔU^+, where the $+$ superscript indicates viscous scaling based on u_* and the

A. Segalini · R. Örlü · P. Henrik Alfredsson
Linné Flow Centre, KTH Mechanics, SE-100 44 Stockholm, Sweden
e-mail: segalini@mech.kth.se

Ian P. Castro
School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, U.K.

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kinematic viscosity, ν. The mean velocity profile of the boundary layer over a rough wall is often assumed to have the same structure as the equivalent smooth case with the offset provided by the roughness function as

$$\frac{U}{u_*} = \frac{1}{\kappa}\ln\left(y^+\right) + B - \Delta U^+ + \frac{2\Pi}{\kappa} W\left(\frac{y}{\delta}\right), \tag{1}$$

with a logarithmic region near the wall and a wake region for $y = \mathscr{O}(\delta)$. The y-origin is located between the valley and the peak of the roughness, at a distance d from the roughness minimum height [1]. Another major difference between the smooth and rough case is associated to the higher value of the wake parameter Π observed over rough surfaces [2].

It is generally believed that the direct effect of roughness can be observed in a layer with size 2-3k, where k is the roughness height, leading to the conclusion that high values of the ratio δ/k are required to reduce the effect of the roughness to the inner region of the boundary layer, which is dominated by viscous effects in the smooth wall case [3]. Away from the wall, and for a roughness with high enough δ/k, the turbulent flow will just be determined by the momentum transferred downward and absorbed by the drag of the roughness elements, a hypothesis usually referred to as Townsend's similarity hypothesis. The validity of such an assumption has been discussed in some recent investigations [2, 4, 5], but at the moment it is the only model available that describes at least part of the distribution of the velocity correlations in the boundary layer.

It is clear that the complete characterization of the flow over rough surfaces is a complicated task where a large number of parameters are involved, most of them related to the roughness characteristics, making any attempt to provide an *a priori* estimation of the turbulence intensity cumbersome. Despite the fact that a significant amount of experimental and numerical data are available, the research community has not been able yet to provide some trend without relying on specific data sets and, in particular, without the possibility to generalize the results.

Recently, Alfredsson *et al.* [6] have proposed a new fit of the streamwise velocity fluctuation profile, viz. a scatter plot between the mean velocity (normalized by an outer characteristic velocity scale, such as the free-stream velocity, U_∞) and the local streamwise turbulence intensity, u'/U, where u' is the streamwise velocity standard deviation. The new way to plot experimental and numerical data for u' yields a collapse of the data over a significant part of the boundary layer and, in a region starting within the logarithmic region out into the wake region, u'/U decreases linearly with U/U_∞: This feature gave the possibility to develop a simple estimation of the streamwise velocity variance profile once the mean velocity profile is given.

In the present work the diagnostic plot method is applied to data from rough surfaces to investigate the possibility that a similar fit might exist in this case as well, leading to some simple relationship between the mean velocity profile and the turbulence intensity. It is expected that the roughness characteristics should modify the plot, but the method should also be able to point out the leading parameters that relate the turbulence intensity with the mean velocity, providing some insight into the physics of the turbulent boundary layer over rough surfaces.

2 Results and Discussions

Since the diagnostic method is still an empirical tool, a large number of experiments have been collected to provide evidence of the observed behavior. These experiments are listed in table 1 where it is shown that a large range of k^+, ΔU^+ and δ_{99}/k has been investigated.

Table 1 Details of the used experimental data

Experiment	Roughness	k^+	δ_{99}/k	ΔU^+
[4]	Sanded surface	8-62	130-162	0.14-4.6
[5]	Mesh	67-260	4-50	8-13.4
[5]	Random blocks	162-681	4.3-15	9.3-12.5
[5]	Grit	32-79	9-30	3-6.4
[8]	Braille	7-22	462-492	0.44-3.43
[9]	Grit	14-108	20-77	2.6-10.0
[10]	2D rods	103	130	13.9
[11]	Cubes	426-474	7-11	12-13.1
[12]	Sandpaper	60-385	16-54	5.2-13.0
[12]	Mesh	28-309	19-109	6.3-13.2
[13]	2D bars	11	160	7.7
[13]	2D bars	56	32	12.7
[13]	Staggered cubes	68	28	10.0

The diagnostic plot of all the available data, plotted regardless of the roughness characteristics and streamwise positions, is shown in figure 1. Each single

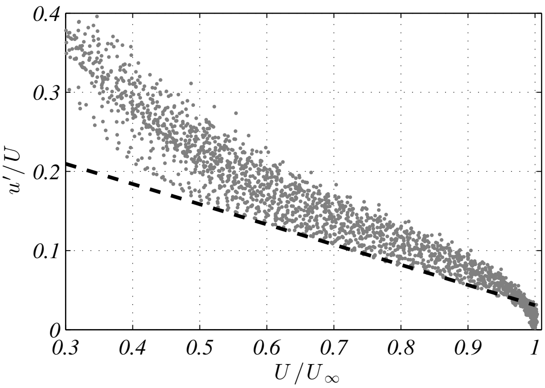

Fig. 1 Diagnostic plot of the available data plotted in traditional form. The dashed line indicates the smooth wall line given by Alfredsson *et al.* [7].

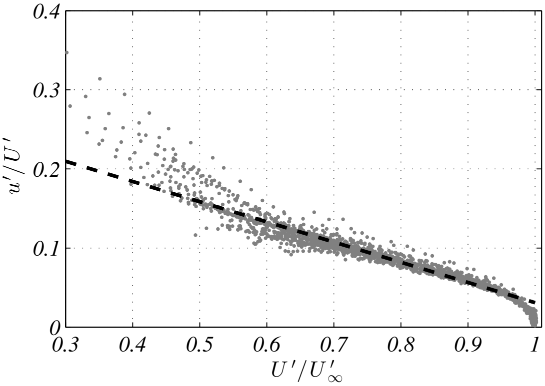

Fig. 2 Diagnostic plot of the available data in the proposed form with $U'^+ = U^+ + \Delta U^+$. The dashed line indicates the smooth wall line found by Alfredsson *et al.* [7].

experiment follows a linear behaviour, but the negative slope of the line appears to increase with the roughness strength. A surprising collapse of the data can, however, be achieved by including the roughness function in the mean velocity, namely by introducing the velocity $U'^+ = U^+ + \Delta U^+$, as shown in figure 2: In this case all the data agree much better, with a scatter that could be related to the uncertainty in the determination of ΔU^+, and overlaps the smooth wall line found by Alfredsson *et al.* [7]. This property is in agreement with Townsend's hypothesis since the variance is the same once the corrected mean velocity profile is the same. The fact that the wake parameter is higher, raises some doubt on the actual validity of Townsend hypothesis that nevertheless seems to be able to describe the leading observation.

By considering that the modified diagnostic plot indicates a scaling relationship, the local turbulence intensity at any mean velocity level, U/U_∞, can be found as

$$\frac{u'}{U} = \frac{U/U_\infty + \Delta U^+/U_\infty^+}{U/U_\infty}\left(a + b\frac{U/U_\infty + \Delta U^+/U_\infty^+}{1 + \Delta U^+/U_\infty^+}\right), \qquad (2)$$

where $a = 0.286$ and $b = -0.255$ are the smooth wall constants given by Alfredsson *et al.* [7]. An example of equation (2) is reported in figure 3 where the good agreement between the measurements and the empirical line is evident.

Despite the different roughness characteristics, figures 1–3 demonstrate that the parameter ΔU^+ (or its equivalent roughness length, y_0, defined by $\Delta U^+ = \kappa^{-1} \ln y_0^+ + B$) is a single measure of the roughness effect to the outer region of the boundary layer. The corrected diagnostic curves overlap with the smooth wall data covering the transitional to fully rough regimes, providing a simple and useful fit to estimate the turbulence intensity in the outer region of the turbulent boundary layer.

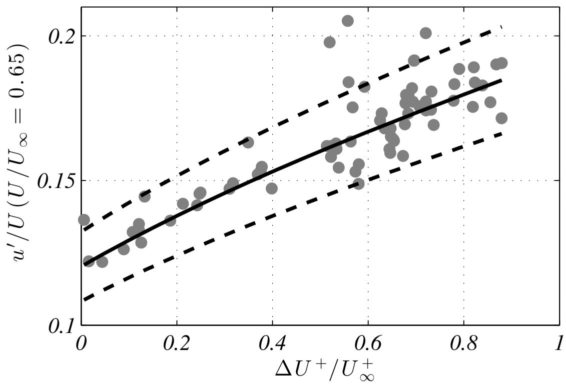

Fig. 3 Turbulence intensity of the available data at $U/U_\infty = 0.65$. The solid line indicates the extension of the smooth wall line of Alfredsson *et al.* [7] by accounting for ΔU^+, while the dashed lines indicate a $\pm 10\%$ deviation from the proposed fit.

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