

Identifying Well-Behaved Turbulent Boundary Layers

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Abstract This paper presents a study focused on the development of zero-pressure-gradient turbulent boundary layers (ZPG TBL) towards *well-behaved* conditions in the low Reynolds-number range. A new method to assess the length required for the ZPG TBL to exhibit *well-behaved* conditions is proposed. The proposed method is based on the diagnostic-plot concept (Alfredsson et al., Phys. Fluids, 23:041702, 2011), which only requires mean and turbulence intensity measurements in the outer region of the boundary layer. In contrast to the existing methods which rely on empirical skin-friction curves, shape-factor or wake-parameter, the quantities required by this method are generally much easier to measure. To test the method, the evolution of six different tripping configurations, including weak, late and strong overtripping, are studied in a wind-tunnel experiment to assess the convergence of ZPG TBLs towards *well-behaved* conditions in the momentum-thickness based Reynolds-number range $500 < Re_\theta < 4000$.

1 Introduction

The problem of establishing canonical conditions in experiments with zero-pressure-gradient (ZPG) turbulent boundary layers (TBLs) has become a relevant one since it is known that there can be important differences in quantities such as the shape factor $H = \delta^*/\theta$ (where δ^* and θ are the displacement and momentum thicknesses, respectively) or in the skin-friction coefficient c_f , due to a flawed experimental design and/or an inadequate inflow and/or development length [10]. These problems are not restricted to experimental studies since, as shown by Schlatter and Örlü [10],

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numerical simulations are also affected by inflow conditions and by the tripping method. For this reason, recent studies such as the one by Marusic et al. [3] have analyzed the effect of different tripping configurations and how the flow evolves towards a canonical state. In their work, Marusic et al. [3] reported the effect of a number of tripping configurations, ranging from a weak tripping to an overstimulated case.

In the light of these findings, the need to establish criteria for the characterization of canonical conditions has emerged as an important challenge. Comparisons of experimental trends of the wake parameter Π and of H with the ones obtained from numerical integration of composite profiles are currently used as a criterion to identify *well-behaved* profiles [2], i.e., not affected by non-equilibrium effects present in the initial development stages. Moreover, Schlatter and Örlü [10] established that TBLs can be considered canonical for $Re_\theta > 2000$ if the transition is initiated prior to $Re_\theta = 300$; using this criterion, good quantitative agreement in integral quantities and higher-order moments between experiments and simulations was found. As a result of the study performed by Marusic et al. [3], it was found that the effect of the tripping mechanism was noticeable up to a streamwise distance of 2000 trip heights, although this conclusion is only applicable to their particular set-up.

All of these methods share one common characteristic: they require extensive measurements to discern whether the flow is canonical/well behaved. For this reason, here we aim at establishing a method to assess the length required for the TBL to exhibit *well-behaved* conditions, without the need to obtain velocity profiles or to measure the friction velocity at several streamwise locations. Our proposed method is based on the diagnostic-plot concept, which has been found to scale the outer layer of TBL flows irrespective of Re [1, 8]. The method will be demonstrated based on hot-wire anemometry measurements that have been performed in the Minimum Turbulence Level (MTL) wind tunnel at KTH Mechanics in which different tripping configurations in a ZPG TBL were studied.

2 Experimental Setup

The measurements were performed in the MTL closed-loop wind tunnel located at KTH Royal Institute of Technology in Stockholm. The tunnel has a 7 m long test section with a cross-sectional area of $0.8 \times 1.2 \text{ m}^2$ with a streamwise velocity disturbance level lower than 0.025% of the free-stream velocity. Measurements were made in the turbulent boundary layer developing over a flat plate suspended 25 cm above the tunnel floor under a zero-pressure-gradient condition that was established through adjustment of the ceiling. All the measurements were performed at a nominal free-stream velocity of 12 m/s. Six different tripping configurations were tested using as a reference the cases studied numerically in Schlatter and Örlü [10], i.e. a combination of weak, late, and strong trippings. The different tripping configurations were placed spanning the full spanwise length of the plate, at streamwise locations in the range $75 < x \text{ [mm]} < 230$ from the leading edge (see Table 1), corresponding

Table 1 Specifications of the tripping configurations including location and respective symbol coding for symbols. The embossed (DYMO) letter ‘V’ points into the flow direction and has a nominal height of 0.3 mm

Tripping characteristics and location	Symbol code	Identification
DYMO ‘V’ @ 75 mm	Red	Weak tripping
DYMO ‘V’ @ 230 mm	Green	Late tripping
DYMO ‘V’ @ 75, 90, 110 mm and 5 mm square bar @ 85 mm	Blue	Strong overtripping
DYMO ‘V’ @ 90, 110 mm and 2.4 mm height turbulator	Black	Optimal 1
DYMO ‘V’ @ 90, 110 mm and 1.6 mm height turbulator	Magenta	Optimal 2
DYMO ‘V’ @ 90 mm	Cyan	Weak/late tripping

to the range $130 < Re_\theta < 260$. A set of 4 streamwise locations was selected for each tripping configuration with few additional stations to match Re_θ , covering a range of $500 < Re_\theta < 4000$. Single-point streamwise velocity measurements were performed by means of a single in-house hot-wire probe with a Platinum wire of 560 μm length and nominal diameter of 2.5 μm . These dimensions provided sufficient spatial resolution to ensure meaningful comparisons of the higher-order turbulence statistics. Care was taken to acquire sufficient measurement points within the viscous sublayer and the buffer region in order to correct for the absolute wall position and determine the friction velocity (as outlined in Örlü et al. [7]). The composite profile by Nickels [5] was used to obtain the free-stream velocity U_∞ and the 99% boundary-layer thickness δ_{99} . Reynolds numbers and integral quantities were then computed using the fitted composite profile.

3 Results and Discussion

Inner-scaled streamwise mean and variance profiles for the various trippings are shown in Fig. 1a, where it can be observed that the near-wall region quickly adapts to that of a canonical TBL [10]. On the other hand, strong variations are noticeable in the outer layer, which indicates that this part of the boundary layer requires longer development lengths to become independent of its specific tripping condition. In particular, the strong-overtripping case shows an outer peak in the fluctuation profile which is produced by the square bar used as a disturbance. In order to determine which of the TBL profiles have reached a canonical state, the Reynolds-number variation of the shape factor and the skin friction (expressed through the inner-scaled free-stream velocity U_∞^+) for all tripping configurations is depicted in Fig. 2 together with the correlations from [4, 6]. Postulating now that *well-behaved* TBL profiles should scale in the diagnostic plot (as suggested in [1, 8]), the same data set is shown in terms of the streamwise turbulence intensity u'/U versus the velocity ratio U/U_∞ in Fig. 3. Excluding, under the aforementioned premise, the profiles that do not

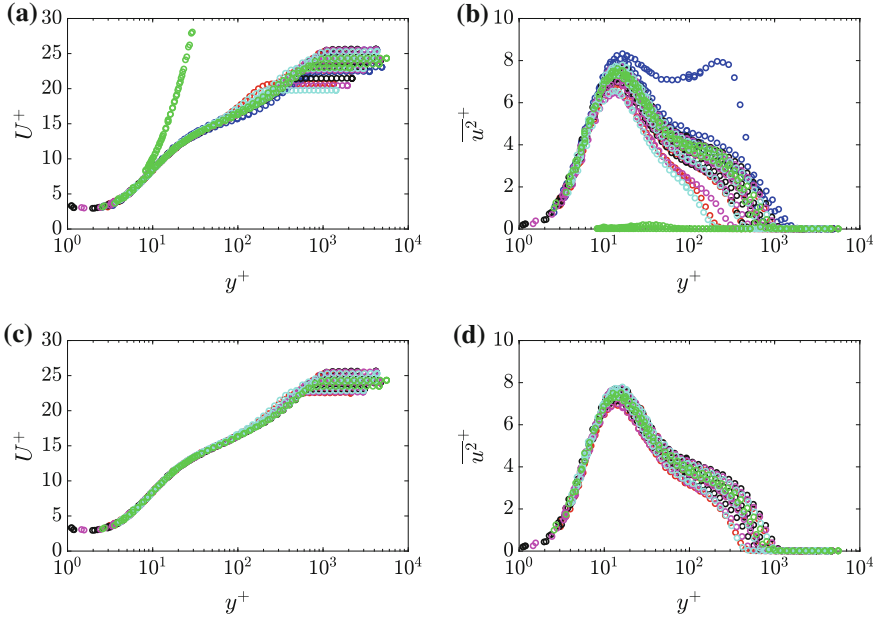


Fig. 1 Inner-scaled **a** mean and **b** variance profile for the entire data set, and **c**, **d** same quantities for the profiles that fulfill the diagnostic-plot scaling in the outer layer. See Table 1 for color code, and Fig. 3 for diagnostic-scaling plots

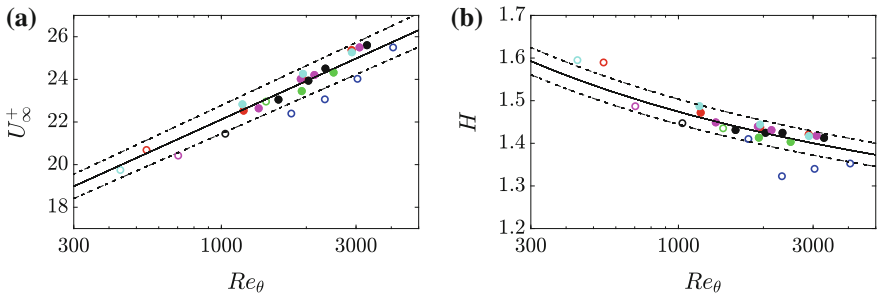


Fig. 2 **a** Shape factor H and **b** inner-scaled free-stream velocity U_∞^+ as function of Re_θ for various tripping configurations. Cases considered as *well-behaved* are further identified through filled circles. *Solid lines* represent correlations from Monkewitz et al. [4] for H and from Nagib et al. [6] for U_∞^+ . *Dashed lines* are common measurement uncertainties, i.e., 3% and 2% in subplots **a** and **b**, respectively

adhere to the scaling in the outer region, especially in the region $0.7 \leq U/U_\infty \leq 0.9$, the diagnostic-plot concept provides a means to discern *well-behaved* TBLs; these profiles are indicated through filled circles in Fig. 2 and their diagnostic scaling is shown in Fig. 3b.

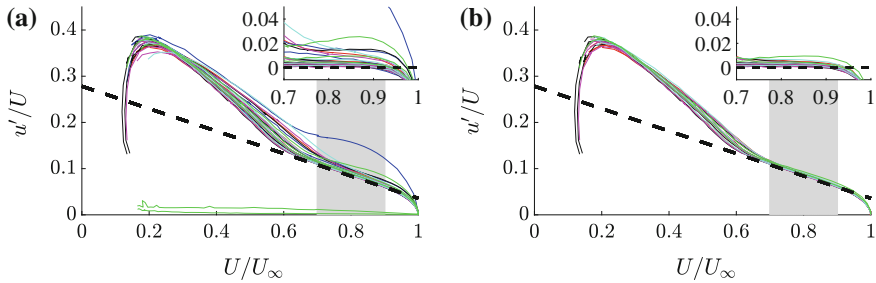


Fig. 3 Streamwise mean U and r.m.s. u' profiles plotted in diagnostic form for **a** the entire data set and **b** only the profiles that follow the diagnostic-plot scaling, i.e., those identified through filled circles in Fig. 2. The dashed line shows (within the shaded range) equation $u'/U = \alpha - \beta U/U_\infty$, with $\alpha = 0.280$ and $\beta = 0.245$. The insets show the difference between the profiles in diagnostic scaling and the diagnostic-curve fit, as a function of U/U_∞

It can be observed that the profiles that satisfy the diagnostic-plot criterion are exactly the ones that follow the reference U_∞^+ and H curves. This indicates that the diagnostic-plot criterion described in [1] is an alternative method to assess whether a particular boundary layer exhibits canonical ZPG TBL conditions. The real advantage of the proposed method is shown, that no full velocity profile measurements, integral quantities, or skin friction measurements are required. Instead a streamwise scan within the outer region of the TBL (preferably through the region of linear behavior in the diagnostic plot, i.e., the shaded area in Fig. 3) is sufficient to identify the location after which the TBL adheres to the diagnostic-plot scaling. To test this assumption, Fig. 4 shows the results of a streamwise scan in the tripping configuration weak/late tripping (see Table 1) while keeping (through an iterative procedure)

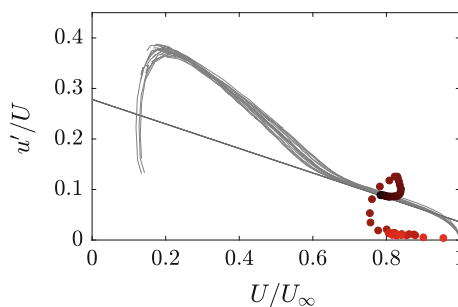


Fig. 4 A methodology based on streamwise scans and diagnostic scaling, used to predict the distance required for the ZPG TBL to exhibit *well-behaved* conditions. The method is illustrated using the tripping configuration denoted as weak/late tripping. Solid lines correspond to the cases of Fig. 3b. All the points are taken with an equidistant streamwise spacings of $\Delta x = 50$ mm, where darker symbols indicate increasing streamwise distance

the probe within the velocity range $0.7 \leq U/U_\infty \leq 0.9$. From the color-coded measurement points (from lighter to darker symbols, where darker indicates increasing streamwise distance) it can be observed how the boundary layer undergoes transition to turbulence with the overshoot in turbulence intensity and then reaches the diagnostic-plot reference curves. Hence, a simple streamwise scan easily diagnostic from which x-location on the TBL behaves in accordance with canonical ZPG TBLs.

Disclaimer Parallel to the present paper, a largely extended and more detailed study has been published by Sanmiguel Vila et al. [9].

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