DOWNSTREAM EVOLUTION OF PERTURBATIONS IN A ZERO PRESSURE GRADIENT TURBULENT BOUNDARY LAYER

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Abstract This abstract examines the evolution of perturbations generated by various trips in a turbulent boundary layer. Measurements taken using hot wire anemometry show that the evolution towards the natural state is strongly dependent on the formation mechanisms of the boundary layer, this being different for different wall normal distribution of the trips' blockage. It is observed that standard boundary layer properties are recovered, after an adaptation region, with 175% higher momentum thickness than the natural case. Two-point measurements with time resolved velocity in the inner region are studied to explore the different formation mechanisms.

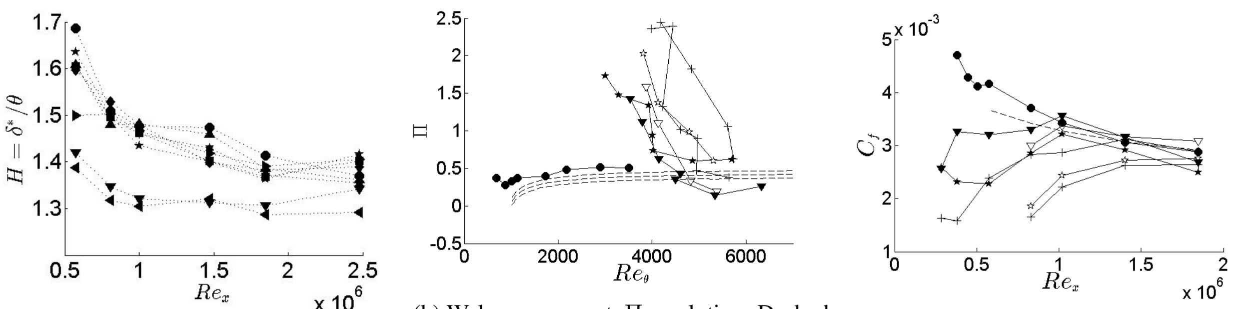
INTRODUCTION AND EXPERIMENTAL SET-UP

Upstream perturbations modify the development of a boundary layer, making it fully turbulent, or thicker than its natural size [3]. These perturbations will evolve with downstream distance (x) towards the natural state of a turbulent boundary layer (TBL), described in [1]. Obtaining a thick TBL in a short distance is of primary importance to the study of high Reynolds number flows in short wind tunnels *only if* asymptotic properties are fully recovered and the trip effects have disappeared. The present objective is to study various spanwise arrays of trips (divided into uniform and non-uniform distribution of blockage) and the effect of the TBL formation mechanism on the recovery distance of natural properties; namely, thickness, log-law, friction coefficient, turbulence intensity, spectra and wake component [1].

Experiments are conducted at Imperial College London in a wind tunnel with test section dimensions of $0.91 \times 0.91\,\mathrm{m}^2$ and $4.8\,\mathrm{m}$ length. A flat plate is mounted to ensure zero pressure gradient. Measurements are taken using constant temperature hot wire anemometry. Various trips (different combinations of spanwise distributed cylinders, [3], and a sawtooth fence, [5]) are located at $x = \{160, 890\}\,\mathrm{mm}$ corresponding to $h/\delta_\gamma \gg 1$ and $h/\delta_\gamma \lesssim 1$ respectively; δ_γ is defined as the first point without turbulence intermittency. The wall shear stress and the wall location are extrapolated from the velocity profile [2] with accuracies $\Delta u_\tau = \pm 1\%$, $\Delta y = \pm 15\,\mu m < \pm 1/2y^+$. Where $y^+ = yu_\tau/\nu$ and $u^+ = u/u_\tau$.

RESULTS: ONE AND TWO POINT HOT-WIRE MEASUREMENTS

Studies with two different trips have been performed: a sawtooth fence and an array of cylinders. The TBL produced with cylinders behaves similarly to the natural case (but with a higher thickness), while the TBL produced by the sawtooth presents different properties (figure 1a). Considering as diagnostic quantities the wake component [1] and the friction coefficient, figures 1b and 1c show that using cylinders allows the standard properties to be recovered in a shorter distance and more accurately. They also show that the parameter h/δ_γ is less important than the downstream distance from the trips. These results suggest a different formation mechanisms for the TBL affecting the evolution of its properties.



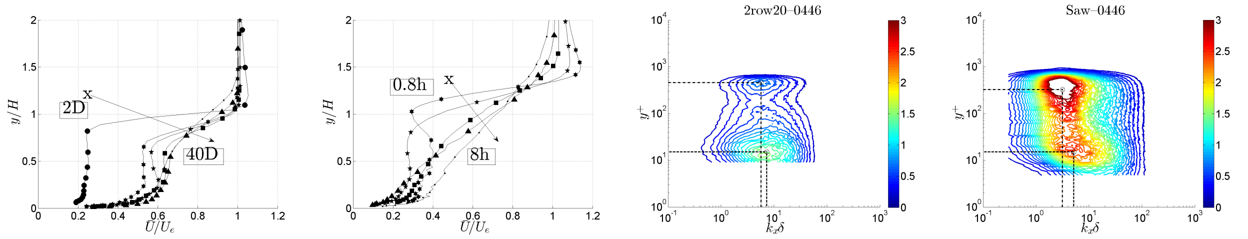
(a) Shape factor, H, evolution

(b) Wake component, Π, evolution. Dashed line given by [1].

(c) Friction coefficient, C_f, evolution

Figure 1: (●): Natural boundary layer. Filled symbols mean $h/\delta_\gamma \gg 1$ and empty symbols are $h/\delta_\gamma \simeq 1$.
($\star$): *2row20*: 2 rows ($\Delta x = 16\,\mathrm{mm}$) of spanwise ($\Delta z = 10\,\mathrm{mm}$) distributed cylinders ($D = 3\,\mathrm{mm}$ $h = 20\,\mathrm{mm}$) [3]
(∇): *Saw*: spanwise ($\Delta z = 20\,\mathrm{mm}$) distribution of vortex generators inclined $40°$ ($h = 20\sin(40°)\,\mathrm{mm}$) [5].
$\{\triangle, *, \triangleright, \square, \diamond, +\} \rightarrow$ various combination of cylinders with similar properties to *2row20*

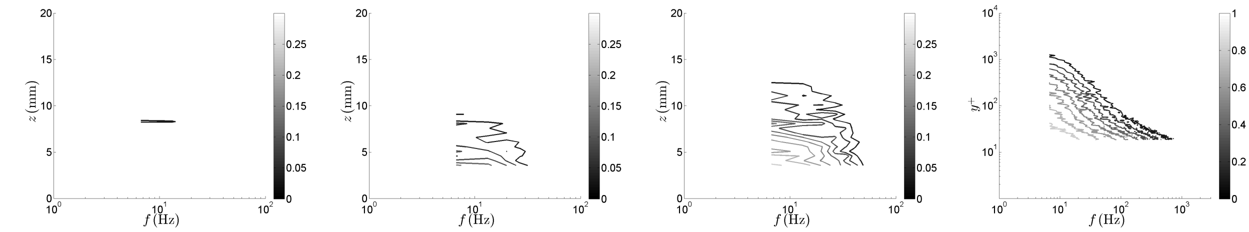
Hot wire measurements in the near field of the trips suggest that the cylinders generate a spanwise periodic combination of wakes (figure 2a). This low momentum highly turbulent flow is seen as the outer flow by the boundary layer growing underneath and it is entrained increasing TBL thickness by augmenting its wake region (figure 1b) without modifying the inner part of the TBL (figure 2c). On the other hand, the sawtooth, due to its non uniform blockage ratio, generates a velocity profile that resembles a boundary layer (figure 2b) but does not reflect its properties (figure 2d). The coherent structures downstream of the trips generate a higher turbulence intensity which delays the appearance of the inner peak (figure 2d). This suggests an imposition of the TBL properties by the wake of the trips contrasting with the wall driven mechanisms starting only 20 diameters downstream of the cylinders. In both cases, the standard properties are recovered downstream of the trips, albeit with a momentum thickness 175% of that observed in the natural case.



(a) Mean velocity. Near field. *2row20* (behind the obstacle) (b) Mean velocity. Near field. *Saw* (behind the obstacle) (c) Normalized premultiplied spectrum *2row20* $x = 446$ mm (d) Normalized premultiplied spectrum *Saw* $x = 446$ mm

Figure 2: Mean velocity $\bar{U}$ and normalized premultiplied spectra $E_{11}(k)k/u_\tau^2$ near the different trips. Dashed lines in **c** and **d** mark the inner peak, $y^+ = 15$ (— — —), and h, the height of the trip (— · —).

Two-point measurements are taken in order to study both formation mechanisms. A marginally elevated hot wire ($6 \leq y_0^+ \leq 10$) allows time resolved measurement of velocity in the inner region. Traversing a second hot wire both in the wall normal and the spanwise directions provides information about two-point correlations studied by the cross spectral density. This will allow us to discern whether the formation mechanism is wall driven (cylinders), or if the artificial imposition of a velocity profile by the sawtooth forces a *top-down* mechanism. Figures 3a, 3b and 3c show the spanwise correlation maps at $x = 0.9$ m using different trips. Turbulent structures are detected covering a spanwise distance similar to the periodicity present on the trips (10 mm for *2row20* and 20 mm for *Saw*). These structures are not seen in the natural case for the same x, and the homogeneity is recovered after the adaptation region. Considering the wall normal correlations, figure 3d shows that, downstream of the adaptation region, the correlation level decreases with increasing y and that for small heights the correlation is extended to higher frequencies, as expected for the natural case. Further studies regarding the modulation of the wall shear stress [4] by the turbulent structures generated by the trips will be presented in order to test the aforementioned hypothesis and provide further answers about the different formation mechanisms.



(a) $\Gamma = f(z)$, $x = 0.9$ m, $y^+ \sim 8$, *Natural* (b) $\Gamma = f(z)$, $x = 0.9$ m, $y^+ \sim 8$, *2row20* (c) $\Gamma = f(z)$, $x = 0.9$ mm, $y^+ \sim 8$, *Saw* (d) Wall-normal $\Gamma = f(y^+)$, $x = 3.9$ m, *Saw*

Figure 3: Spanwise (**a, b, c**) and wall-normal (**d**) variation of normalized cross-power density spectra, $\Gamma = \frac{|cpsd(u_1,u_2)|^2}{psd(u_1)psd(u_2)}$.

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