Downstream Evolution of Perturbations in a Zero Pressure Gradient Turbulent Boundary Layer

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Abstract This paper examines the evolution of perturbations generated by various trips in a zero pressure gradient turbulent boundary layer. Measurements taken using hot-wire anemometry show that the evolution of the boundary layer towards the natural state is strongly dependent on the trip geometry. In particular the mechanisms creating the boundary layer appear to depend primarily on the wall normal distribution of blockage ratio, recovering the natural properties more rapidly for a uniform distribution of blockage (wall normal cylinders) than for non-uniform blockage (sawtooth fence). The relative size of the trip with respect to the boundary layer is shown to be a second order effect. Standard behaviour (characterized by the skin friction coefficient, C_f, the wake component, Π, and the shape factor, H) is recovered successfully $500D \sim 75h$ downstream, presenting 175% higher momentum thickness, θ, than the natural case for the same downstream distance.

1 Introduction

Upstream perturbations modify the development of a boundary layer, making it fully turbulent [4], or thicker than its natural size [3]. These perturbations will evolve with downstream distance (x) towards the natural state of the 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 the influence of various trips (divided into uniform and non-uniform wall normal distributions of blockage) located at different downstream positions, on the TBL properties (thickness, log-law, friction coefficient, wake component [1], turbulence intensity, shape factor and spectra) and the effect of the TBL formation mechanism on the recovery distance of natural properties.

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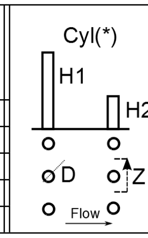
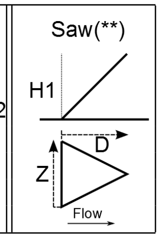
2 Experimental Set-up

Experiments are conducted at Imperial College London in a wind tunnel of $0.91 \times 0.91\,\mathrm{m}^2$ section and $4.8\,\mathrm{m}$ length with $U_e = 10\,\mathrm{ms}^{-1}$. A wooden flat plate provided with a flap is mounted vertically spanning the whole height of the tunnel ensuring zero pressure gradient. Measurements are taken using constant temperature anemometry. Sampling at $100\,\mathrm{kHz}$ for $30\,\mathrm{s}$ and low-pass filtering at $30\,\mathrm{kHz}$ allow resolution of $0.2 < t^+ = tu_\tau^2/\nu < 0.5$. The different trips described in table 1 are located at $x = \{160, 890\}$ 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. Velocity profiles are taken for $0.9\,\mathrm{m} < x < 3.9\,\mathrm{m} \Leftrightarrow 0.57 \cdot 10^6 < Re_x = U_e x/\nu < 2.42 \cdot 10^6$ (far field), and $\{2, 4, 6, 10, 20, 40\}$ diameters downstream of the trips (near field). The wall shear stress and the wall location are extrapolated from the velocity profile [2] with accuracies $\Delta u_\tau = \pm 1\%$, $\Delta y = \pm 15\,\mu m < \pm 1/2 y^+$. Where $y^+ = y u_\tau/\nu$ and $u^+ = u/u_\tau$.

Table 1 Trips description. $Z = 10$mm for cylinders [3] and $Z = 20$mm for Saw. $h = max\{H1, H2\}$.

	1row10	*1row20*	*2row10*	*10and20*	*20and10*	*2row20*	*2stagger*	*Saw Inv*	*Saw*	*Natural*
Type	Cyl(*)							Saw(**)		-
Symbol	△	∗	▷	□	◇	⋆	+	◁	▽	○
H1(mm)	10	20	10	10	20	20	20	15.3	15.3	0
H2(mm)	0	0	10	20	10	20	20	-	-	0
D(mm)	3	3	3	3	3	3	3	-12.8	12.8	0





3 Results

Experiments measuring the far field created by all the trips from table 1 located such that $h/\delta_\gamma \gg 1$ show that: (i) Different arrays of cylinders generate a thicker TBL than the natural case (fig. 1A) and with the same properties (fig. 1B,C). (ii) The thickness of the TBL created is a function of the height of the highest cylinder, not of the number of rows nor their order. (iii) The sawtooth fences generate an even thicker TBL (fig. 1A) but with a different shape factor (fig. 1B). (iv) It also generates an acoustic perturbation in the freestream ($y/\theta = 19$) up to 20 times stronger than the natural case at a fixed Strouhal number $St^\star = f^\star \theta/U_e \sim 0.019$ which persists for more than 2m (fig. 1C). These observations suggest different formation mechanisms for the TBL using cylinders or sawtooth. Both are exhaustively studied henceforth.

As seen in fig. 3A,B cylinders generate a spanwise periodic combination of jets and wakes which becomes uniform after $40D$. This low momentum, highly turbu-

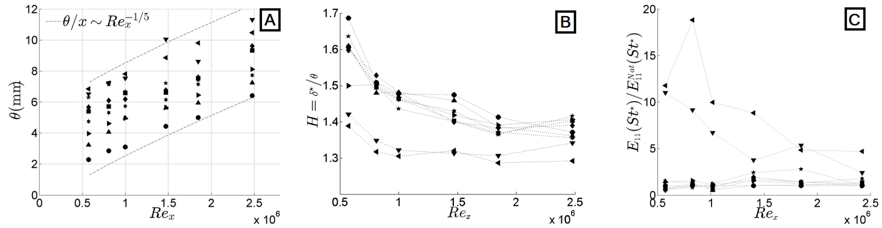


Fig. 1 (A) Momentum thickness (θ) evolution. (B) Shape factor (H) evolution. (C) Relative magnitude of spectra at $y/\theta = 19$ ($y \gg \delta_\gamma$) for $St^\star$. Symbols are given in table 1

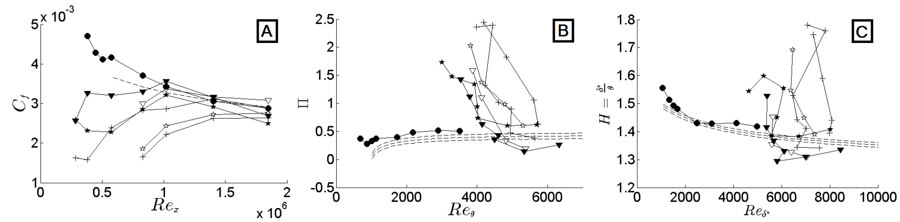


Fig. 2 (A) Friction coefficient (C_f) evolution. Dashed line is 1/5th correlation. (B) Wake component (Π) evolution. Dashed line by [1]. (C) Shape factor (H) evolution. Dashed line by [1]. Symbols are given in table 1. Filled symbols are $h/\delta_\gamma \gg 1$ and white symbols are $h/\delta_\gamma \lesssim 1$.

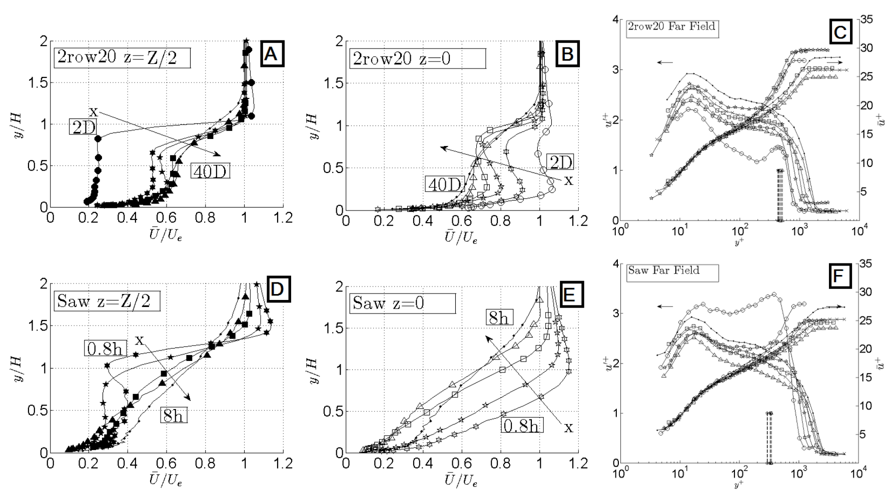


Fig. 3 Velocity profiles for Near ($z = \{0, Z/2\}$) and Far Field using *2row20* and *Saw* trips.
$\{$A,B$\}$→[$\circ * \star \Box \triangle \cdot$]→$\hat{x}$ =[$2D, 4D, 6D, 10D, 20D, 40D$] from the trip (*2row20* Near field).
$\{$D,E$\}$→[$* \star \Box \triangle \cdot$]→$\hat{x}$ =[$0.8h, 1.2h, 2h, 4h, 8h$] from the trip (*Saw* Near field).
$\{$C,F$\}$→[$\circ * \star \Box \triangle \times \cdot$]→$x$ =[0.46, 0.6, 0.9, 1.3, 1.6, 2.2, 2.9]m from leading edge (Far field).
Dashed line marks the non-dimensionalized height of the obstacle, $h^+ = hu_\tau/\nu$.

lent flow is seen as the outer flow by the TBL growing underneath and it is entrained increasing TBL thickness by augmenting its wake region. This generates a development region (until $500D \sim 75h$) where the wake component (Π)[1], friction coefficient, (C_f) and shape factor (H), present non standard behaviour (fig. 2). It also shows that the effect of h/δ_γ is secondary compared with the distance from the trips.

On the other hand, the sawtooth, due to its non uniform blockage ratio in the wall normal direction, generates a velocity profile downstream of the gaps ($z = 0$) which resembles a boundary layer but does not reflect its properties (fig. 3E). Downstream of the obstacle ($z = Z/2$) a recirculation and a strong tip vortex are seen. Although these two spanwise periodic regions become uniform after $8h$, the turbulence intensity is artificially high until $70h$, where the inner peak starts to appear (fig. 3F). Spectral data (not included for brevity) shows a shedding from the cylinders at $St = fD/U_e = 0.19$ disappearing before $20D$. The broadband turbulence generated by the recirculation and the tip eddies in the sawtooth covers $0.1 < St = fh/U_e < 0.5$ and persists for more than $40h$. Downstream of the location where the inner peak (at $y^+ = 15$) is developed no extraordinary spectral features are seen. Note that the turbulence intensity in the case of cylinders increases with x; whereas in the sawtooth case it initially decreases from a high value near the trips, before increasing again with x after a longer development region.

4 Conclusions

Different arrays of spanwise distributed trips generate perturbations which evolve downstream of them. This study shows that the standard properties of the TBL can be recovered at a distance downstream of the obstacle which depends on the trip geometry. In particular, the wall normal distribution of blockage has been demonstrated to play the main role while the relative size h/δ_γ seems to be secondary. The recovery of standard TBL properties is shown to be faster and more effective when using arrays of cylinders than when using the sawtooth due to the different formation mechanisms. The use of these trips can increase the TBL thickness by up to 175%; thus generating a high Reynolds number TBL in a shorter distance than the natural case while maintaining the same properties.

References

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