Drag reduction in a turbulent boundary layer using periodic blowing through one array of streamwise slits

Yinzhe Li[1] and Yu Zhou[1,#]

[1]*Institute for Turbulence-Noise-Vibration Interaction and Control, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen, China*

[#]Corresponding author: zhouyu@hitsz.edu.cn

Abstract Active drag reduction of a turbulent boundary layer has been experimentally investigated using periodic blowing through one array of streamwise slits. Local skin-friction drag exhibits a strong dependence on control parameters, including the blowing amplitude A^+ and frequency f^+. A maximum drag reduction of almost 70% has been achieved at x^+=33 downstream of the actuators. The near-wall structure under control are measured using smoke-wire flow visualization, hot-wire and PIV techniques. All the results point to a pronounced change in the structure of the boundary layer and a significant increase of the mean energy dissipation rate.

EXPERIMENT SETUP

Active control of a turbulent boundary layer for drag reduction has long been an important research area in fluid mechanics and attracts more attention in recent years due to ever rising fuel costs and increasing concern of emissions. Bai et al. [1] demonstrated that the skin friction drag in a turbulent boundary layer can be reduced locally by 50% based on wall-normal oscillations generated by an array of piezo-ceramic actuators. This investigation is a continuation of the work and explores the effectiveness of drag reduction based on unsteady blowing through an array of streamwise slits.

A 4.8-m-long and 0.8-m-wide flat plate, tripped at the leading edge, was placed in a low-speed wind tunnel to generate a turbulent boundary layer (Fig. 1a). An array of 9 streamwise slits was placed 3 m downstream of the leading edge, where the boundary layer disturbance thickness, shape factor and Reynolds number based on the momentum thickness were 0.085m, 1.45 and 1450, respectively, at an incoming flow velocity of 2.4m/s. Each slit is 20mm long, 0.5mm wide and 3 mm thick (Fig.1b). The centre-to-centre spacing between slits is 2 mm. The idea of the slit size and separation originates from the arrangement of the piezo-ceramic actuators. Air from a compressor goes through a filter, a pressure relief valve, a throttle valve, a flow meter and an electromagnetic valve before reaching a plate of 30 mm × 120 mm, with 8 equally distributed holes of 10 mm in diameter, and a contraction with an area ratio of 6, which are mounted to ensure the uniformity of jets through slits. The electromagnetic valve with a 20% duty-cycle is characterized by a frequency range of f = 5 ~ 400Hz. The outlet velocity U_{out} of the jets through slits, its distribution at the different locations of the slit and its frequency are all measured carefully using a Dantec hotwire anemometer at various volume flow rates Q and frequencies f. The time-averaged jet velocity $\overline{U_{out}}$ is 0.5m/s, corresponding to $A^+ = \overline{U_{out}}/u_\tau = 4.6$, where superscript + denotes normalization by wall units. The f^+ range is $7 \sim 560 \times 10^{-3}$. The wall shear stress was estimated from the slope of the velocity profile in the viscous layer measured using a single hotwire. The hotwire measurement was conducted at ($x^+ = 33 \sim 460$, $z^+ = 0$) and ($z^+ = -90 \sim 90$, $x^+ = 33$).

(a) Flat plate	(b) Actuator and its installation
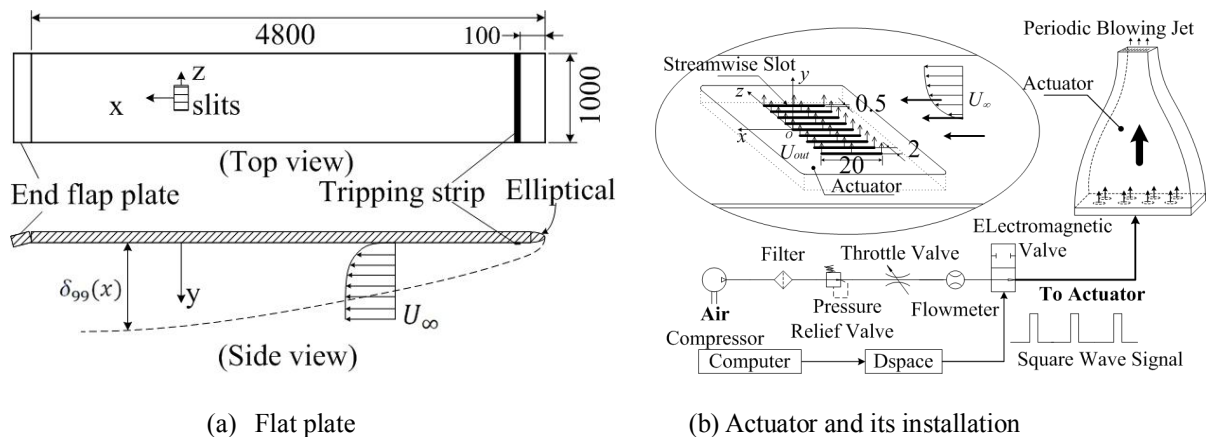
Figure 1. Experimental setup (the length unit is mm)

RESULTS

The drag change $\delta_{\tau_w} = (\overline{\tau_w} - \overline{\tau_{w0}})/\overline{\tau_{w0}}$, where $\overline{\tau_w}$ and $\overline{\tau_{w0}}$ are time-averaged wall shear stress with and without control, respectively, depends on both A^+ and f^+ (Fig 2). δ_{τ_w} initially decreases with blowing amplitude increasing and then increases or appears unchanged with further increasing A^+ (Fig 2a). On the other hand, at a given A^+, δ_{τ_w} initially drops rapidly with increasing f^+ and then levels off (Fig 2b). δ_{τ_w} depends on the streamwise measurement location. For $A^+ = 0.66, f^+ = 420\times10^{-3}$, δ_{τ_w} reaches almost 70% at $x^+ = 33$ and drops slowly, not fully recovered until at $x^+ = 460$ (not shown). In contrast, the drag fully recovers by $x^+ = 160$ in Bai et al. [1]. Nevertheless, the present control exhibits similarity to that deployed by Bai et al. [1] such as the δ_{τ_w} dependence on A^+ and f^+.
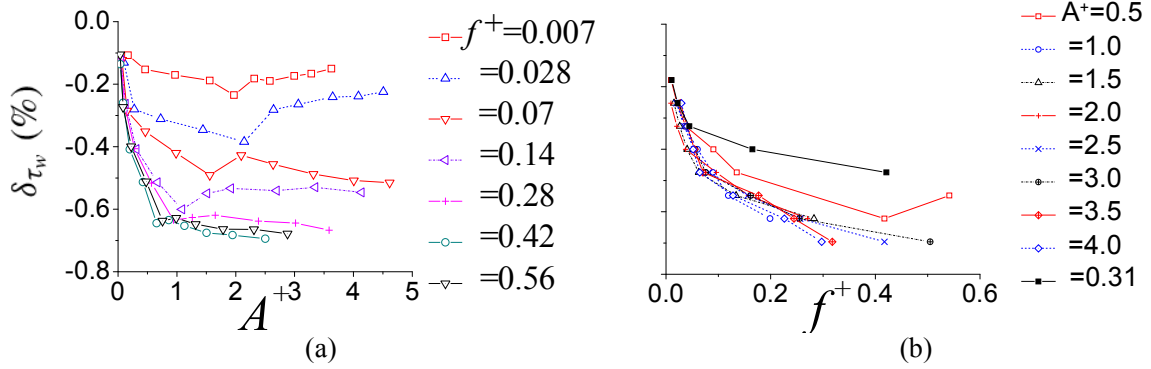

Figure 2. Dependence of δ_{τ_w} on A^+ and f^+.

Extensive PIV, hotwire and flow visualization measurements have also been conducted. It has been found that the large-scale near-wall streaky structures are greatly weakened in size (e.g. Fig 3), fluctuating velocities are reduced appreciably, Taylor's microscale shrinks by more than one half (not shown), and the energy dissipation rate is greatly enhanced. The observations point to the fact that the control interrupts the turbulence production cycle on one hand and promotes enormously the energy dissipation rate on the other hand, thus promoting relaminarization and resulting in drag reduction.
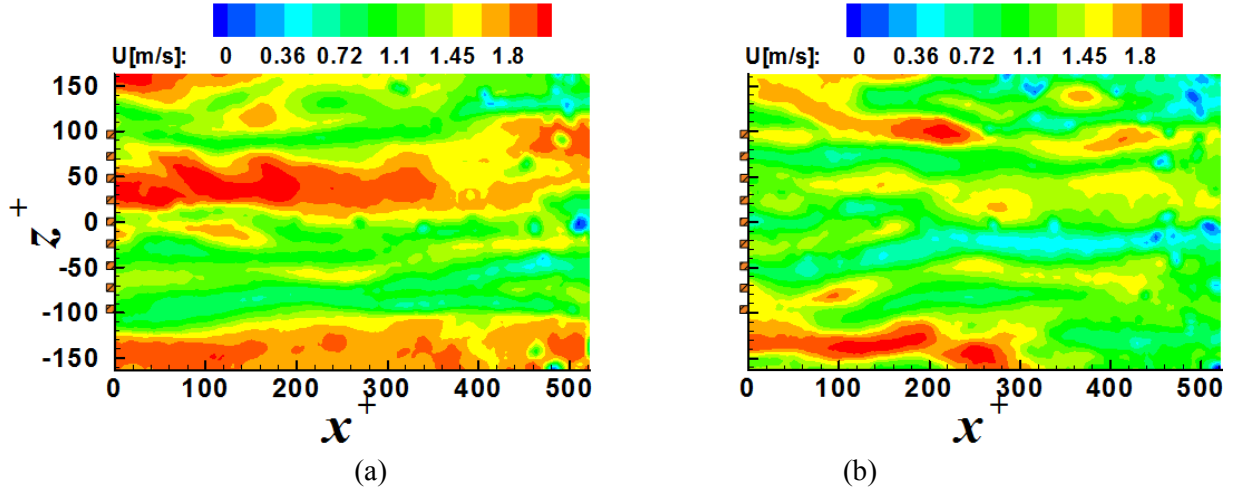

Figure 3. The iso-contours of instantaneous streamwise velocity in the xz plane (PIV measurement, $Re_\theta = 1450$, $y^+ = 13$): (a) natural boundary layer, (b) perturbed ($A^+ = 0.66, f^+ = 420\times10^{-3}$). Flow is left to right. Small squares indicate the streamwise slits, whose trailing edge is at $x^+ = 0$.

References
[1] H. L. Bai, Y. Zhou, W.G. Zhang, S. J. Xu, Y. Wang and R. A. Antonia. Active control of a turbulent boundary layer based on local surface perturbation. Journal of Fluid Mechanics, **750**: 316-354, 2014