SKIN FRICTION DRAG REDUCTION USING UNSTEADY BLOWING THROUGH ONE ARRAY OF STREAMWISE SLITS

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INTRODUCTION

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.

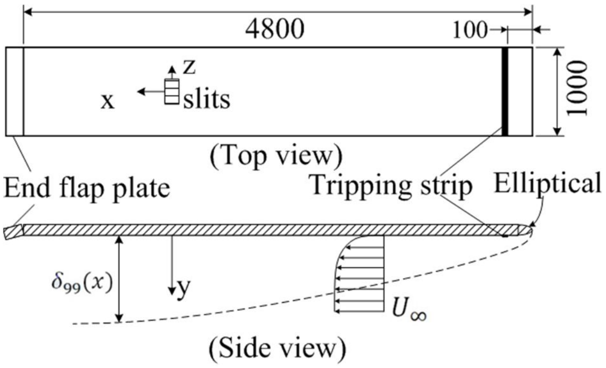

Figure 1: Boundary layer flat plate (the length unit is mm).

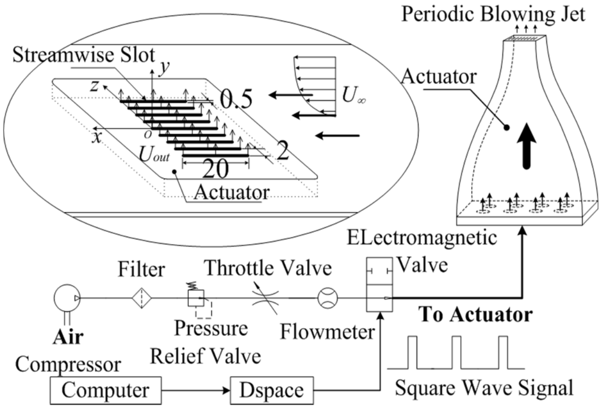

Figure 2: Actuator and its installation (the length unit is mm).

EXPERIMENTAL SETUP

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.1). 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 3mm thick (Fig.2). The centre-to-centre spacing between slits is 2mm. The idea of the slit size and separation originates from the arrangement of the piezo-ceramic actuators (Bai et al. [1]). 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 ~ 560×10^{-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 ~ 460, z^+ = 0) and (z^+ = -90 ~ 90, x^+ = 33).

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.3). δ_{τ_w} initially decreases with blowing amplitude increasing and then increases or appears unchanged with further increasing A^+ (Fig.3). On the other hand, at a given A^+, δ_{τ_w} initially drops rapidly with increasing f^+ and then levels off (Fig.4). 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^+.

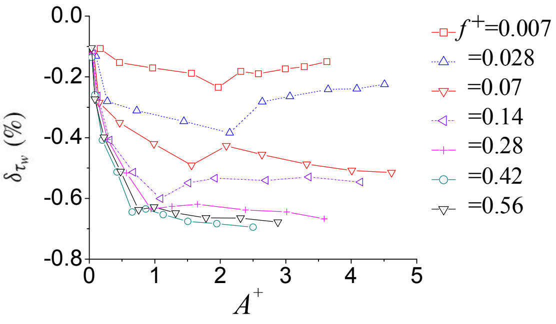

Figure 3: Dependence of δ_{τ_w} on A^+ at different f^+

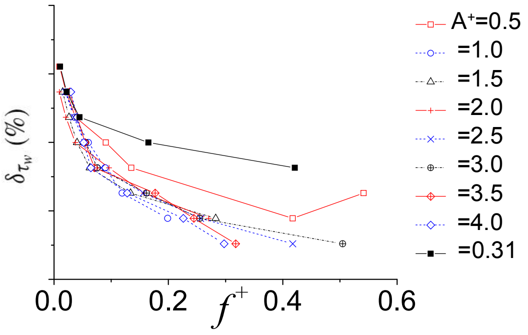

Figure 4: Dependence of δ_{τ_w} on f^+ at different A^+

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.5), fluctuating velocities are reduced appreciably, Taylor's microscale shrinks by more than one half (not shown), and the energy dissipation rate is greatly enhanced which is also observed by Tardu[2] and Laadhari et al.[3] whose results showed great drag reduction along with a decrease in the Taylor microscale . 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.

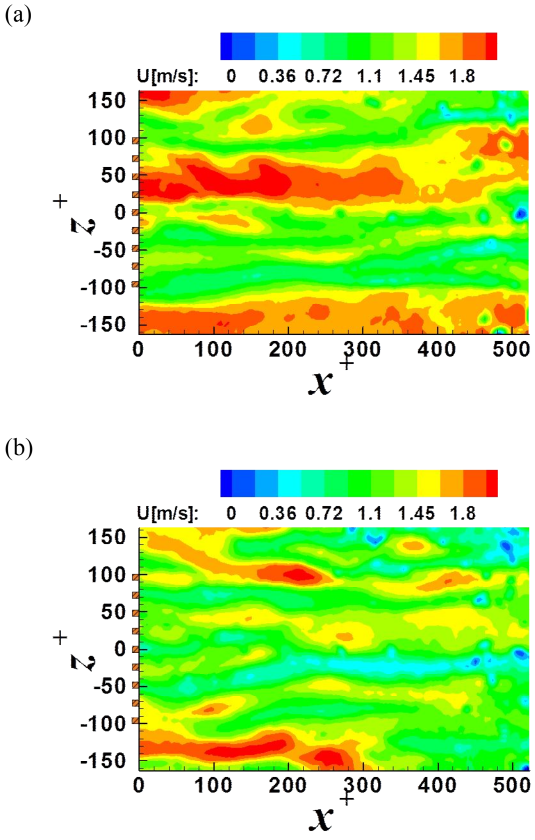

Figure 5: The iso-contours of instantaneous streamwise velocity in the xz plane (PIV measurement, Re_θ= 1450, y^+ = 13): (a) natural boundary layer, (b) perturbed (A^+= 0.66, f^+ =420×10^{-3}).(Flow is left to right. Small squares indicate the streamwise slits, whose trailing edge is at x^+ = 0.)

Acknowledgment

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