Modification of Near-wall Turbulence for Drag Reduction by Spanwise Oscillating Lorentz Force[1]

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ABSTRACT

The results of an experimental investigation on the effect of a spanwise oscillating Lorentz force on the near-wall turbulent structures for drag reduction are presented in this paper. Comparing with the case of turbulent control by spanwise wall oscillation, a parameter called "equivalent spanwise wall velocity" $W^+_{eq}=StT^+/(2\pi Re_\tau)$, is defined and emphasized as a virtual spanwise wall velocity scale under Lorentz force oscillation. It is shown that when $W^+_{eq}\approx$ 10-15, up to 30-40% skin frictional drag reduction could be achieved just at the downstream of the control area. Meanwhile, an oscillation amplitude investigation suggests that to achieve maximum skin friction reduction, the oscillation Lorentz force should be able to shift the near-wall streamwise vortices into spanwise direction by a peak to peak displacement of about 100 wall units during each period. A conceptual model to explain the mechanism for drag reduction under the spanwise Lorentz force oscillation is also presented.

Key Words: Turbulent boundary layer, drag reduction, spanwise oscillation, Lorentz force

1. Introduction

The exploration of using Electromagnetic force (Lorentz force), which can act upon the conductive fluids in the form of a body force to achieve flow control and drag reduction in turbulent boundary layers, has been studied by many researchers over the last decade.[1-6] By using Electro-Magnetic Turbulence Control (EMTC), it is easy to produce some flow control strategies such as wall normal blowing/suction,[1] streamwise blowing[5] or spanwise oscillation by only simply altering the arrangement of electrodes and polarities of the magnets without changing the boundary wall.[6] EMTC was first used for transition and separation control, in which the Lorentz forces were mainly act in the streamwise direction.[5] Nosenchuck and his group seem to be the first group to explore the possibility of achieving drag reduction by EMTC. In their experiments, the Lorentz force was mainly created along the wall-normal direction. Although up to 50% drag reduction has been reported[1] but no repeatable results reported from the other researchers. It was followed by many studies, both experimentally and numerically, focusing on playing with the working directions of the Lorentz force, trying to find the optimum conditions to achieve drag reductions.[2-6]

Meanwhile, with more understanding of the near-wall coherent structures and turbulence self-regeneration sequences, the strategies for drag reduction tend to modify or disturb any part of this sequence of the near-wall activities.[7] Among many of the turbulence control techniques, a spanwise oscillating excitation for drag reduction has attracted many attentions and it has been considered as an effective way to disturb this near-wall regenerating turbulence sequence and give skin friction reduction.[8,9] Hence, turbulence control by spanwise wall oscillation has been studied extensively in the last ten years and 25-40% skin friction reduction has been reported.[10-15] Choi et al.[11] implied that the turbulent skin friction reduction with spanwise wall oscillation can be optimized with a non-dimensional spanwise wall velocity $W_0^+ = (\Delta z/2)\omega/u_\tau$, and nearly 45% drag reduction can be obtained in the turbulent boundary layer at an optimum value of $W_0^+\approx 15$.

With the inspiration from wall oscillation, turbulence control by a spanwise oscillating Lorentz force has been developed. Berger and Kim et al. of the UCLA group seems to be the first to present a very detailed DNS study on Lorentz force oscillation at different frequencies and Reynolds numbers.[6] An optimum spanwise velocity scale $StT^+/(2\pi Re_\tau)$ = 10 was also suggested by Berger et al., and under which up to 40% drag reduction can be achieved. Experimental studies of spanwise Lorentz force oscillation have been done by Pang

[1]All the experiments of the present research were carried out at the University of Nottingham as a Ph.D. research project under the supervision of Dr K-S Choi (1999-2003). Future research of developing actuators by applying spanwise oscillation for separation control on a wind section is carrying on at AIST, Japan.

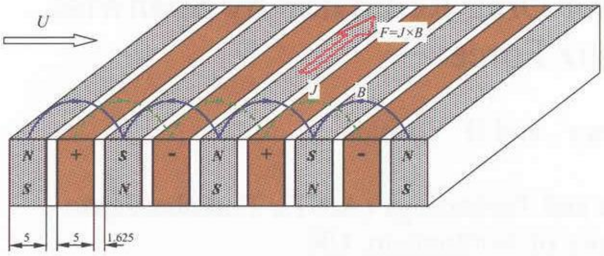

Figure 1: Configuration of electrodes and magnets to create Lorenz force in parallel to wall surface, normal to flow direction. By switching the polarity of the electric current, spanwise-oscillating Lorenz force field was created.

and Choi [16,17] in an open water channel. After realizing the importance of the near-wall spanwise velocity scale in a spanwise oscillatory excitation, the spanwise velocity profiles under Lorentz force oscillation and wall oscillation were studied and an equivalent spanwise wall velocity $W^+_{eq} = StT^+/(2\pi Re_\tau)$ has been introduced.[16] The introduction of W^+_{eq} makes it possible to link wall oscillation and Lorentz force oscillation together and make comparisons under the same spanwise *wall* velocity scale. It was shown that when $W^+_{eq} \approx$ 10-15, up to 30-40% skin friction reduction can be found just at the downstream of the controlled area.[17] This shows a good agreement with the experimental results on spanwise wall oscillation, in which an optimum spanwise wall velocity $W_0^+ = 15$ was suggested.[11] This seems to suggest that wall oscillation and Lorentz force oscillation may work in a very similar mechanism for drag reduction. Very similar as the investigations by Pang and Choi[16,17], an experimental investigation on spanwise Lorentz force oscillation was done by Breuer et al.[18] and Park et al.[19] in a pipe flow by using PIV and direct drag measurement. Their recent results showed that 10% drag reduction has been achieved. From a scaling analysis, Breuer et al.[18] implied that the scale of oscillating Lorentz force should match the inertial force of fluid in order to effectively modify the near-wall structures. An optimal Stuart number *St* was also suggested by Breuer et al. as $St = JBa/(\rho u_\tau^2) = aRe_\tau/(hT^+)$. Although the scaling system quoted here is slightly different from Berger et al.[6] and Pang et al.[17], this seems to confirm that under the same Reynolds number, the optimal *St* should be inversely proportional to oscillation period T^+. Park et al.[19] argued that the drag reduction measured in their experiments may be partially counteracted by the enhancing flow speed, implying the real drag reduction may be bigger than the measured one. Breuer et al.[18] also implied that because only mean effects of skin frictional drag were measured over a test surface with and without Lorentz force oscillation, some local drag reduction is likely much higher than 10%.

This paper is aiming to show more evidences of the effect of Lorentz force oscillation on the near-wall coherent structures by analyzing the optimum amplitude of Lorentz force oscillation. The drag reduction mechanism under Lorentz force oscillation will also be discussed.

2. Experimental Setup

The present experiments were performed in a 7.3 meter long close-loop open-water channel with a working section of 600×300 mm. The free stream velocity of the present experiments is set as 0.14 m/s, with a zero pressure gradient along the length of the working section. A 4-meter long test plate with 20:1 ellipse leading edge was placed in the channel. The boundary layer was tripped just after the leading edge by an artificial surface roughness (about 10 mm high) to ensure a fully developed turbulent boundary layer over the working area on the test plate. To reduce corrosion problems in the channel system, CuSO4 was chosen and it was introduced into the flow by slot-injection through a 0.5 mm wide and 250 mm long slot with a nearly tangential speed of about 0.025 m/s. From this injection, a suitable layer with strong conductivity is produced just above the surface of test plate without soiling the rest of water. The conductivity was reduced along the test plate from original 1.0 S/m to 0.247 S/m at the measurement position (324 mm downstream of the injection slot) as a result of diffusion. The diffusive layer thickness, the wall-normal distance from the wall where the conductivity reduce to half of the maximum value, was 3.2 mm (y^+=19) at this location. The added momentum to the flow from the injection was only 0.042% of the momentum of the turbulent boundary layer, therefore the effect of injection on the boundary layer profile is negligible. The test plate material is made of perspex with a replaceable part for EMTC control actuators and $CuSO_4$ injection slot to fit in. The turbulent intensity in this open-channel is about 1% by placing screens and honeycombs in the channel and up-stream tank just before the test plate.

The total EMTC area is made up by 16 small Electro-magnetic (EM) arrays, which were placed in the replaceable part of test surface and kept flush to the wall surface. This will cover a streamwise x^+ up to 1770 and spanwise z^+ up to 1357. Each EM actuator is made of 5 mm wide, 10 mm high and 50 mm long rectangular bar of NdFeB permanent magnets with 1.2 T remanence and copper electrodes of the same size in an interleaved way with 1.63 mm thick insulator in between. This will correspond to an effective size of magnets and

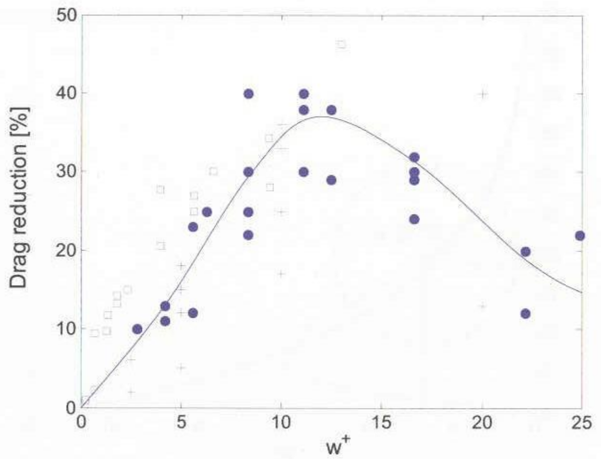

Figure 2. Drag reduction against $W^+_{equi}=StT^+/(2\pi Re_\tau)$ at all the Lorentz force oscillation conditions; Comparisons with data from Choi (2002) and Berger et al. (2000) are also shown in the figure.
(●), Present experimental data; (+), Berger & Kim et al. (2000); (□), Choi (2002); ( ), fitted curve for the present experimental data

electrodes of a = 6.63 mm with a penetration depth Δ^+ = 12.4 (Fig. 1). By switching the polarity of direct current to the electrodes, the direction of the spanwise Lorentz force can be altered periodically, which will introduce an oscillatory flow motion in the near-wall region of the turbulent boundary layer. It was observed that the electrolysis bubbles, which appeared in most cases of EMTC experiments, were greatly reduced throughout the experiments. During the experiments, copper (Cu), one of the productions of the electro-chemical reaction in the $CuSO_4$ solution, will be deposited on the copper electrodes without changing the surface characters of the electrodes.

Single component streamwise velocity measurements were made by Dantec 56C CTA system and a single, miniature boundary type hot-film probe-Dantec 55R15. This fiber-film sensor is a Nickel film deposited on a 70 μm diameter quartz fiber. Overall length is 3 mm, and sensitive film length is 1.25 mm. Film is protected by a quartz coating with approximately 2 μm thickness, which can protect the film to work in this conductive and corrosive solutions after $CuSO_4$ injection in the systems. The hot-film was operated in constant temperature mode with an over-heat-ratio of 1.05, with which the bubble generation from the film surface could be effectively reduced. At the same time, the wall proximity effect due to heat conduction from the probe to the wall surface was not observed in the present study at least for $y^+ > 1$ because of the application of low over-heat-ratio over a nonconductive test plate in high thermal conductive fluid (water), whose thermal conductivity is 23.5 times greater than that of air and approximately three times greater than that of the Perspex test plate. Data from the anemometer system were sampled at a rate of 50 Hz using an IOTech ADC 488/8S analog-to-digital (AD) converter. The probe is mounted to a wall normal (y-axis) traverse system, which is computer controlled via a Digiplan step-motor controller. The wall normal movements are made with a resolution of 1.25 μm.

All the measurements were confined at 5 mm downstream of the EM actuator arrays, where no noticeable changes to the hot-film signal due to the interference of the electromagnetic fields were noticed. The estimated mean magnetic strength at the surface of the actuator is B_0 = 0.78 T. By changing the voltage applied to the EM actuators between V_0 = 3.2 and 12.9 V, the current density $J_0 = (\pi/4a)\sigma V_0$ was set between 94 and 376 A/m2 according the conductivity σ at the hot-film measurement position (5 mm downstream of the EM array), giving the St from 105 to 422 in the present experiments.

3. Results and Discussion

For more information of experimental setup, boundary layer profiles with and without Lorentz force oscillation, skin friction measurements and optimization, please read reference 17 and 23.

A. Amplitude measurement

As mentioned earlier, an "equivalent spanwise wall velocity" $W^+_{eq} = StT^+/(2\pi Re_\tau)$ plays an important role in finding the optimum conditions for turbulence control under Lorentz force oscillation and an optimum value of W^+_{eq} = 10-15 was suggested after experiments at different combination of St and T^+ (Fig. 2). Since the main power consumption for Lorentz force oscillation will be determined by the current which has been applied during the excitation, this seems to imply that to achieve drag reduction with lower power consumption, a smaller St and a bigger oscillation period T^+ (lower oscillating frequency) are preferred. However, how does the oscillation amplitude change with frequency? How important of the oscillation amplitude to the Lorentz force oscillation? The following section may give us some clue.

The oscillation amplitudes at different oscillating frequencies (0.25, 0.33, 0.5, 0.66 and 1.0 Hz) have been measured by a flow visualization method and the results are shown in Fig. 3. During this experiment, the free stream velocity is kept at 0.14 m/s and the non-dimensional Lorentz force St is also kept constant at 210 (based on u_τ at uncontrolled case). The amplitude of the oscillation was measured by reading the peak to peak displacement

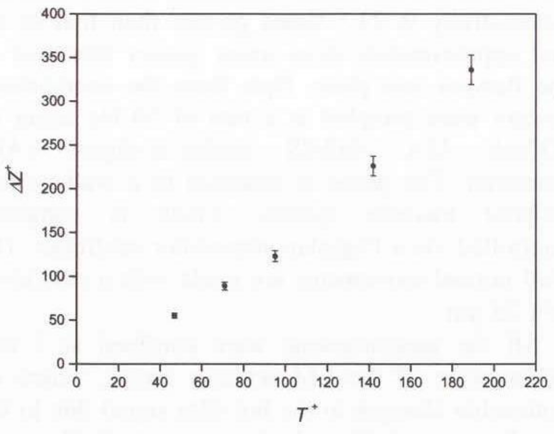

Figure 3: Nondimensional peak to peak displacement Δz^+ of the near-wall streaks under Lorentz force oscillation at different oscillation frequencies (*St*=210)

of one streak structure in one circle of Lorentz force oscillation. With the help of 1 mm grids pasted on the wall surface, 20 sets of amplitude were measured from which an average was determined. Since the streak structures in the visualization pictures are considered as collections of local low momentum structures, we can assume that the observed amplitude of the streaky structures is the oscillation amplitude of the near-wall coherent structures, where the centre of the streamwise vortices with low speed is considered as a collection of the dye for visualization.

Figure 3 presents the non-dimensional peak to peak displacements of the near-wall structures against nondimensional oscillation period T^+. The trend in Fig. 3 suggested a nonlinear relationship between Δz^+ and T^+ under same *St*: higher frequencies result in much lower oscillation amplitudes, this suggested when the frequency is greater, the flow will oscillate with much lower amplitude since the inertial force is too large to overcome, hence resulting in a weaker spanwise disturbance to the flow, and vice verse. It can be found that the peak to peak oscillating displacement is $\Delta z^+ \approx 55$ (about 8 mm) when the oscillating frequency was set at $T^+ \approx 47$ (1 Hz); when oscillating frequency is reduced to $T^+ \approx 189$ (0.25 Hz), a bigger peak to peak oscillating displacement of $\Delta z^+ \approx 340$ (about 49 mm) was observed.

From Fig. 3, if we choose one point which has been suggested as one of the optimum conditions for Lorentz force oscillation: $St = 210$ and $T^+ = 97$ under the present experimental conditions, a spanwise velocity scale can be estimated by $W^+ \approx 2\Delta z/T^+=2.6$. This spanwise velocity scale can be taken as the spanwise oscillation velocity of the centre of the streamwise vortices under the oscillating Lorentz force. If we fit this spanwise velocity scale into the

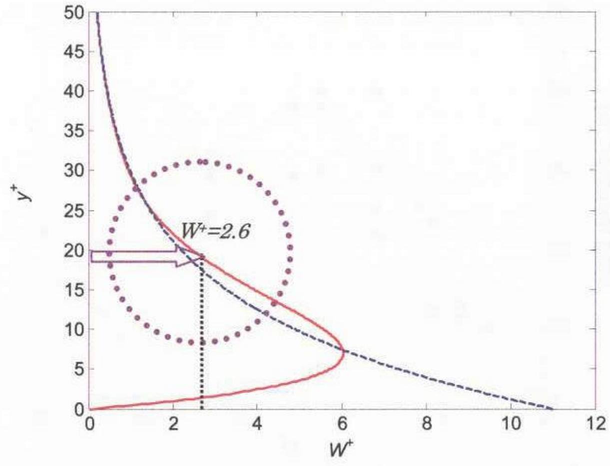

Figure 4: Spanwise velocity profile under the Lorentz force oscillation. *Solid line shows the envelope of spanwise velocity profile calculated by Berger et al. (2000); dashed line shows the calculated spanwise velocity profile when an equivalent wall velocity W^+_{eq} is introduced. (Pang et al. 2003); dotted circle shows the average location and size of near-wall streamwise vortices*

spanwise velocity profile under Lorentz force oscillation,[6] it can be noticed that the centre of the streamwise vortices is located at about $y^+ = 20$ (as shown in Fig. 4). This prediction of the location of the streamwise vortices agrees well with the DNS results,[6,21] in which they suggested the centre of the near-wall streamwise vortices in the turbulent boundary layer is located at about $y^+ = 15$-25. In Fig. 4, the spanwise velocity profile calculated by a simplified model[16] was also plotted for comparison with an "equivalent spanwise wall velocity" W^+_{eq} at $y^+ = 0$. It can be noticed that the spanwise velocity of the center of the near-wall streamwise vortices is about ¼ of the wall velocity W^+_{eq}, implying the centre of the streamwise vortices will oscillate with an amplitude of about ¼ of the *wall* amplitude.

B. Equivalent spanwise wall amplitude A_0^+ under Lorentz force oscillation

An "equivalent spanwise wall amplitude" can be deduced from the "equivalent spanwise wall velocity":

$$A_0^+ = \frac{W_0^+ T^+}{2\pi} = \frac{St \cdot (T^+)^2}{4\pi^2 \mathrm{Re}_\tau} \quad (1)$$

If we substitute all the *St* and T^+ combinations of the present experiments into Eq. (1), a relationship between "equivalent spanwise wall amplitude" A_0^+ and reduction of skin friction can be established as shown in Fig. 5. From Fig. 5, it can be noticed that there exist a higher drag reduction region (about 30% skin friction reduction) when the nondimensional spanwise *wall* amplitude is around

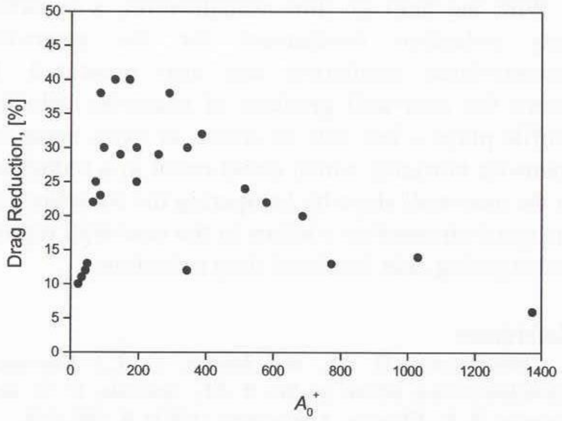

Figure 5: Drag reduction against "equivalent spanwise wall amplitude" A_0^+ at all the present Lorentz force oscillation conditions

200 (between 100 and 300). This will correspond to an optimum peak to peak *wall* displacement Δz^+ of about 400 (two times of the amplitude), which will be capable of moving the streamwise vortices into spanwise direction at a peak to peak amplitude of about 100 according to the previous discussions. Since the mean distance between the streamwise vortices is about 100,[21] these results seem to imply that to achieve effective disturbance to the near-wall streamwise vortices for drag reduction, a spanwise oscillation excitation should be able to move the coherent structures at a displacement same as the mean distance between the near-wall streamwise vortices, which is about 100 wall unit. This was also suggested by Choi et al.[15] in an experimental study of spanwise wall oscillation.

C. Mechanism Investigation

A conceptual mechanism for the spanwise-wall oscillation was first presented by Choi et al.,[15] in which they argued that a negative spanwise vorticity created in the near-wall region of the boundary layer during both negative and positive spanwise motion of the wall oscillation causes a reduction in the streamwise velocity in the near-wall region by hampering the stretching of the quasi-streamwise vortices in the near-wall region, leading to a reduction in the streamwise vorticity and the near-wall burst.

From the flow visualization pictures[17, 23], it can be noticed that: the streak structures are twisted into the spanwise directions when the oscillation force is applied; the spacing between streaks is increased by about 50% and the population/frequency of the streaks is reduced; appearance frequency and duration of the sweep events have been reduced when passing through the electromagnetic arrays.

The similarities between the oscillating Lorentz force case and oscillating wall case seem to suggest these two turbulence control strategies could have

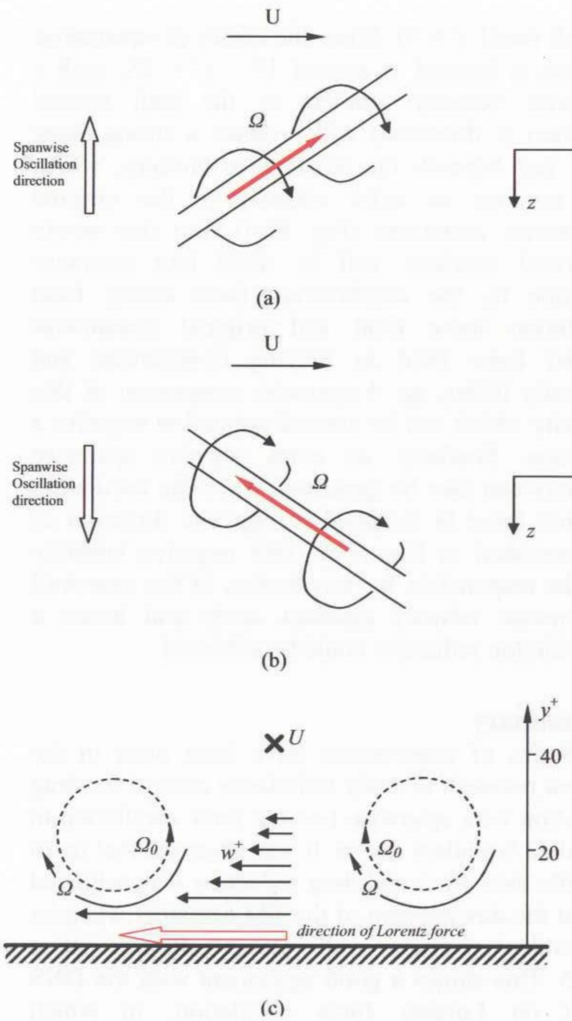

Figure 6: A schematic model shows how an extra negative spanwise vorticity can be generated to the original streamwise vorticity under the oscillating Lorentz force. *(a) Lorentz force is acting in upwards; (b) Lorentz force is acting downwards; (c) Possible spanwise velocity distribution beneath the streamwise vortices under Lorentz force oscillation. An extra vorticity Ω could be generated by this spanwise velocity gradient, where Ω_0 the original streamwise vorticity. This extra vorticity will be twisted into spanwise diection as moving downstream with a negative spanwise component as shown in Fig. 6 (a) and (b).*

very similar mechanism. Fig. 6 shows a schematic model that demonstrates how an extra negative spanwise vorticity to the near-wall turbulent structures (streamwise vortices) could be generated when the shear layer is skewed both into the negative spanwise direction and into the positive spanwise direction. As shown in Fig. 6(a), when the oscillating force is acting upwards in the picture, a shear layer acting in the same direction will be generated. From the profiles of spanwise velocity field generated by oscillating Lorentz force as shown in Fig. 4, it can be noticed that the maximum spanwise velocity will increase as approaching close to wall (until $y^+ \approx 7$). Since the centre of streamwise vortices is located at around $15 < y^+ < 25$, such a spanwise velocity gradient in the wall normal direction (y direction) will produce a strong shear layer just beneath the streamwise vortices, which will produce an extra vorticity to the original streamwise structures (Fig. 6(c)). But this newly generated vorticity will be tilted into spanwise direction by the combination force acting from oscillation force field and original streamwise inertial force field as moving downstream and gradually lifting up. A spanwise component of this vorticity which can be noticed pointed to negative z direction. Similarly, an extra negative spanwise vorticity can also be generated when the oscillating Lorentz force is switched to opposite direction as demonstrated in Fig. 6(b). This negative vorticity will be responsible for a reduction of the near-wall streamwise velocity gradient du/dy and hence a skin-friction reduction could be achieved.

4. Summary

Series of experiments have been done in the present research to study turbulence control for drag reduction with spanwise Lorentz force oscillation in turbulent boundary layers. It was observed that up to 30-40% skin frictional drag reduction was achieved just at the downstream of the EM actuators when an "equivalent spanwise wall velocity" W^+_{eq} is set at 10-15. This shows a good agreement with the DNS result on Lorentz force oscillation, in which $StT^+/(2\pi Re_\tau) = 10$ was suggested as the optimal conditions for drag reduction. This result is very similar to the turbulent drag reduction by spanwise wall oscillation, where a spanwise wall velocity was suggested as a key parameter to describe the amount of drag reduction, with a similar optimal spanwise wall velocity $W_0^+=15$ was reported. Our experiments showed Lorentz force oscillation works at similar drag reducing mechanism as spanwise wall oscillation but with a slightly lower efficiency. It was shown that the near-wall mean velocity gradient reduced by 30-40% and the turbulence intensities in the near-wall region remain unchanged except for a 16% increase around $y^+ = 12$; the higher moments of turbulence statistics like skewness and kurtosis were increased near the wall when $St = 210$ and $T^+ = 97$ in the present experimental conditions.

A discussion on the amplitude suggested the importance of an oscillation amplitude scale also need to be considered apart from focusing on an optimum spanwise *wall* velocity. An "equivalent spanwise wall amplitude" was first defined and the experimental results suggested an optimum value for this *wall* amplitude is around 200, which is capable of moving the near-wall turbulent structures at a peak to peak displacement of about 100 wall units.

With the help of flow visualization, a possible drag reduction mechanism for the spanwise Lorentz-force oscillation was also presented. It seems the near-wall gradient of spanwise velocity profile plays a key role to create an extra negative spanwise vorticity, which could result in a reduction in the near-wall slope by hampering the stretching of the quasi-streamwise vortices in the near-wall region, hence giving skin frictional drag reduction.

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