Turbulent boundary-layer control with plasma actuators

By Kwing-So Choi*, Timothy Jukes and Richard Whalley

Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

This paper reviews turbulent boundary-layer control strategies for skin-friction reduction of aerodynamic bodies. The focus is placed on the drag-reduction mechanisms by two flow control techniques—spanwise oscillation and spanwise travelling wave, which were demonstrated to give up to 45 per cent skin-friction reductions. We show that these techniques can be implemented by dielectric-barrier discharge plasma actuators, which are electric devices that do not require any moving parts or complicated ducting. The experimental results show different modifications to the near-wall structures depending on the control technique.

Keywords: boundary layers; flow control; turbulence; drag reduction; plasma actuators

1. Introduction

Although there is still an ongoing debate on the self-sustaining mechanism within turbulent boundary layers and the interaction between different turbulence structures [1,2], it is generally accepted that most turbulent energy production takes place during the near-wall turbulence events, such as the sweeps and ejections [3]. It is, therefore, important to understand the turbulence structures and their behaviour during these events in order to be able to manipulate the boundary-layer flows effectively for skin-friction drag reduction.

We can imagine the turbulent boundary-layer structure as an assembly of hairpin vortices of different sizes, which are distributed quasi-periodically in time and space [4]. Since the hairpin vortices are convected in the boundary layer with their legs attached to the wall [5], the hairpin legs are elongated to form the quasi-streamwise vortices. The sweep events to bring the high-speed flow [6] can be found on the downwash side of the hairpin legs, while the ejection events are found on the upwash side of the legs [7]. Low-speed streaks are seen within the viscous sublayer [8], pumping up the low-speed fluid in between the elongated legs of hairpin vortices. Hairpin legs can be observed either singly or in pairs in turbulent boundary layers [9].

The sweep events are responsible for the turbulent skin-friction drag [10,11] when the high-momentum fluid is splashed onto the wall surface. Therefore, we can reduce the turbulent skin-friction drag by suppressing the sweep events in the...
near-wall region. This can be done by directly controlling the quasi-streamwise vortices. Alternatively, one can stabilize the low-speed streaks, remove the high-speed region or destroy the hairpin heads. In other words, controlling some of the turbulence structures in turbulent boundary layers may lead to a suppression of sweep events, thereby leading to a reduction in skin-friction drag.

For example, Schoppa & Hussain [12] created weak streamwise vortices within a turbulent channel flow (only 6% of the centre velocity is required for this control) in an attempt to reduce the skin-friction drag. The large-scale, cross-flow motion set up by these vortices seems to have stabilized the low-speed streaks, which led to drag reductions of up to 20 per cent. However, an experimental study that has been carried out with a similar configuration [13] failed to substantiate their direct numerical simulation (DNS) results.

Carlson & Lumley [14] deployed an active Gaussian bump in order to obtain turbulent skin-friction reductions. They pushed the high-speed streaks away from the wall with the bump, spreading the surrounding low-speed fluid. This momentarily reduced the skin-friction drag of the turbulent channel flow. A similar strategy was adopted in wind tunnel studies using MEMS sensors and actuators [15] with some success.

Choi et al. [16] used the opposition control of near-wall turbulence structures, where the sweeps and ejections are counteracted by blowing and suction from the wall surface, respectively. The detection of the turbulence events provided the necessary information for the active control, which weakens the quasi-streamwise vortices responsible for the sweep events. Skin-friction drag reduction of up to 25 per cent was obtained from this technique. The basic concept of this control technique was experimentally confirmed by Rebbeck & Choi [17,18].

An active drag-reduction technique by controlling the outer layer structures of the turbulent boundary layer was developed by Kang & Choi [19]. This is similar in concept to opposition control of near-wall structures discussed above. Although the control parameters were not optimized in this study, their experimental results suggest that the skin-friction drag can be reduced by the direct intervention of hairpin vortices. It is believed that the circulation around the hairpin legs (quasi-streamwise vortices) was reduced after the hairpin heads were destroyed by the control jet, which led to a turbulent drag reduction.

Jung et al. [20] carried out a DNS study of a turbulent channel flow with spanwise wall oscillation. When the non-dimensional period of oscillation was set to \( T^+ = T\nu^2 / \nu \approx 100 \), skin-friction drag was reduced by 40 per cent. The spatial coherence between the quasi-streamwise vortices and the low-speed streaks was disrupted by the spanwise wall oscillation, reducing the skin-friction drag [21]. Choi et al. [22] observed that the quasi-streamwise vortices were twisted during the wall oscillation, reducing the streamwise stretching of the vortices. This weakened the sweep events, which resulted in the skin-friction drag reduction.

Du & Karniadakis [23] investigated a unique control technique using spanwise travelling waves. It was shown that the spanwise travelling waves collect the low-speed fluid and spread it over the wall surface as the waves are propagated in the spanwise direction. As a result, the low-speed streaks are amalgamated to create wide low-speed ribbons. Streamwise travelling waves of spanwise velocity were studied by Quadrio et al. [24], combining the spanwise oscillation and travelling-wave control techniques. Further details of this technique are reviewed by Quadrio [25] in this Theme Issue.
Turbulent boundary-layer control

The Lorentz forcing was used for turbulent boundary-layer control in many DNS studies [26,27]. There was also a lot of experimental work using electromagnetic actuators [28–30] to complement these studies. Since the Lorentz forcing requires electrically conductive media such as sea water, it is not easily applicable to aeronautics. In this paper, we demonstrate that the spanwise oscillation and travelling-wave techniques can be implemented by dielectric-barrier discharge (DBD) plasma actuators in air at atmospheric conditions.

2. Experimental set-up

(a) DBD plasma and actuators

DBD plasma actuators have recently become a topic for flow control as they offer a unique ability to create a body force close to the wall in atmospheric pressure airflows. They are purely electric devices that do not require any moving parts or complicated ducting. The plasma actuators are very simple, fast-acting and can be manufactured as sheets to be adhered to the desired surface. A review of plasma actuators for aerodynamic applications was recently given by Moreau [31] and Corke et al. [32].

DBD plasma actuators for flow control are usually composed of two electrodes separated by a dielectric layer with typical thickness of around 1 mm, as shown in figure 1. One electrode is exposed to the airflow and the other one is encapsulated between the dielectric and the aerodynamic body surface. By applying a high-voltage AC signal, the plasma appears over the surface, which induces an electric wind (to the right in figure 1). These devices usually operate at frequencies between 50 Hz and 500 kHz and the required voltage is typically a few kilovolts. Commonly, they have been applied to flow separation applications with extensive studies being performed over airfoils, which is reviewed by Corke et al. [33] in this Theme Issue.

In this experimental investigation, we study two types of plasma actuators for boundary-layer control: spanwise oscillation and travelling wave. For both cases, electrode sheets were photochemically etched from a copper-clad Mylar sheet (250 μm thick, dielectric constant $\varepsilon = 3.1$). These were adhered onto a removable plate with dimensions $408 \times 337$ mm ($x^+ = xu_T/\nu = 2050$, $z^+ = 1850$), then flush mounted into the wind tunnel test plate 1.9 m from the leading edge.

Each sheet for the spanwise oscillation study had 75 individual plasma actuators aligned in the streamwise direction to produce forcing in the spanwise direction. The electrodes exposed to the airflow had dimensions $370 \times 1$ mm.
Typically $l_p^+ = 40$ (8 mm), $t_p^+ = 2$ (5 ms), $T_p^+ = 40$ (95 ms). Hot-wire measurements taken at the location are shown by dotted line HW. HV, high voltage.

$(x^+ = 1850, z^+ = 5)$, and protruded by 17 μm ($y^+ = 0.09$) from the wall. Velocity measurements were taken at a distance of 15 mm ($x^+ = 7$) downstream of the trailing edge of the plasma to avoid destructive arcing between the electrodes and the probes [34]. We used two sets of plasma actuators for this work. One set was oriented to create wall jets in the $+z$-direction, while the other set produced jets in the $−z$-direction (figure 2). The spanwise oscillating flow was created by activating each electrode set alternately using a two-channel high-voltage power supply. The plasma was formed by applying a voltage of magnitude $E = 6.8$ kV$\text{p−p}$, at frequency $f = 19$ kHz. The driving voltage and frequency were chosen based on our previous results for plasma actuators in quiescent air [34], so that we expected the spanwise-induced velocity would be nearly optimum for spanwise wall oscillation [35].

The plasma actuator sheet used in the spanwise travelling-wave experiment consisted of 24 copper electrodes, powered by a set of high-voltage sinusoidal RF inputs. The upper and lower electrodes were 2.5 and 6 mm ($z^+ = 13$ and 30) in width, respectively, and had an active length of 338 mm ($x^+ = 1730$). The four-phase, spanwise travelling-wave actuator sheet had two different forcing configurations, unidirectional and bidirectional. Unidirectional forcing actuated in one direction per phase, bidirectional forcing actuated in two directions per phase, with each travelling wave forcing over a wavelength, $\lambda_p = 100$ mm ($\lambda_p^+ = 500$).

Figure 3 shows a schematic of the unidirectional forcing configuration that is reported in this paper. The spatial and temporal scales used in the experiments are based on the conditions studied by Xu & Choi [30], in which a 30 per cent reduction in turbulent skin-friction drag was obtained using Lorentz forcing. For the data presented here, the sinusoidal voltage input to the plasma power supplies was fixed at $E = 7$ kV$\text{p−p}$ with a frequency of $f = 25$ kHz and applied with a forcing period of $T_p = 208$ ms ($T_p^+ = 82$), requiring up to 12 power supplies.

Phil. Trans. R. Soc. A (2011)
**Turbulent boundary-layer control**

Figure 3. Schematic of spanwise travelling-wave excitation to show (a) cross section of the plasma actuators and (b) plasma timing. $\lambda_p^+ = 500$ (100 mm) and $T_p^+ = 82$ (208 ms).

**(b) Wind tunnel tests**

The study was performed in a closed-return, low-speed wind tunnel. The test section was 3 m long and had an octagonal cross section of dimensions $508 \times 508$ mm. The turbulent boundary layer was developed over a smooth flat plate set in the upper part of the test section where the streamwise pressure gradient was nearly zero. The flat plate was 3 m long and 22 mm thick, with a super-elliptic shape leading edge with a semi-major axis of 75 mm. An adjustable flap was attached at the trailing edge and set to prevent leading-edge separation. The boundary layer was tripped to fix the transition point using an array of 3 mm diameter rods, 10 mm high. These were placed 100 mm downstream of the leading edge and covered a streamwise distance of 60 mm. Boundary-layer measurements were taken 2.2 m further downstream of the trip. The free-stream velocity was set at $U_\infty = 1.75 \text{ m s}^{-1}$, with turbulence intensity of 0.3 per cent. The turbulent boundary-layer thickness was $\delta = 90$ mm at the measurement station, where the viscous sublayer thickness was around 1 mm. The Reynolds number based on friction velocity was $Re_f = 475$, the Reynolds number based on momentum thickness was $Re_\theta = 1000$ and the shape factor was $H = 1.46$.

Hot- and cold-wire measurements were made within the turbulent boundary layer using a Dantec 56C series anemometry system. Typically, a Dantec 55P15 boundary-layer-type probe was used in constant temperature mode to measure the streamwise velocity component. In addition, a Dantec 55P31 cold-wire probe was used to take temperature measurements within the boundary layer, which was operated in constant current mode. Measurements of the wall-normal and spanwise velocity components were also made using two specially

*Phil. Trans. R. Soc. A* (2011)
manufactured sub-miniature cross wires. The free-stream velocity and the free-stream air temperature were simultaneously recorded and the hot-wire data were corrected for any drift in these conditions. In addition, the hot-wire measurements were corrected for any thermal influence of the plasma based on temperature measurements with the cold-wire probe. The friction velocity was obtained by the Clauser plot method where the log region was matched to that of Schlichting [36]. This value of \( u_t \) obtained with this method was within 5 per cent of the value obtained by least-squares linear fitting of the hot-wire data in the viscous sublayer.

Time-resolved particle image velocimetry (PIV) from TSI (Shoreview, MN) was used to study the travelling wave, which consisted of a Photron Fastcam SA-1 camera, New Wave Research Pegasus PIV laser and a TSI 9307-6 oil droplet generator. The laser was aligned in the \( x-z \) plane parallel to the wall at \( y = 1 \text{ mm (} y^+ = 5 \) in the centre of the DBD plasma sheet, with a field of view of \( 100 \times 100 \text{ mm (} x^+ = 500, z^+ = 500 \). Olive oil droplets with a nominal size of 1 \( \mu \text{m were used to seed the flow through three flush-mounted spanwise slots upstream of the DBD plasma sheet. Image pairs were taken at 750 Hz, with the time delay between frames being typically 200–400 \( \mu \text{s. Data processing was performed using INSIGHT 3G software from TSI using a cross-correlation algorithm to generate vectors over a 32 \times 32 \) interrogation area with 50 per cent overlap to an accuracy of 3–5\% [37]. Experiments in quiescent air were conducted using a similar time-resolved PIV system, consisting of a pulsed copper vapour laser and a Photron Fastcam SA-3 camera. Here, glycerine droplets with nominal size of 1 \( \mu \text{m were used as the seeding particles. The laser sheet was aligned with the actuator mid-span illuminating the \( z-y \) plane. Image pairs were taken at a frame rate of 500 Hz, with the time delay between frames being typically 200–400 \( \mu \text{s.

3. Results

(a) Induced flow by plasma actuators

A series of visualization images of the plasma-induced flow by spanwise oscillation in quiescent air are shown in figure 4. Plasma is created on solid black electrodes with force in the positive \( z \)-direction at \( t/T_p = 0 \) prior to frame (i), and at \( t/T_p = 2\pi \) in frame (iv). This is followed by plasma on open black electrodes in frame (ii) with forcing in the negative \( z \)-direction at \( t/T_p = \pi \). Upon initiating plasma on the solid black actuators, sets of counter clockwise rotating vortices are created that travel in the positive \( z \)-direction, as shown in frames (i) and (iv). These increase in size as they move along the wall, driven by the positive spanwise wall jets that occur by plasma [38]. In contrast, clockwise-rotating vortices are created when activating the open black actuators that are driven by wall jets in the opposite direction, as shown in frame (iii). The spanwise flow oscillation is thus created by repeating this cycle, where a complex interplay between new and old vortices is observed. The plasma consumes the old vortex from directly above, bringing it towards the wall and into the newly forming vortex, as displayed in frames (ii) and (iv). We confirmed using PIV measurements that the vortices in each frame are still rotating for at least 70 ms \( (t/T_p > 2\pi/3 \) in figure 4) and are not a manifestation of convected smoke tracers.

Phil. Trans. R. Soc. A (2011)
Instantaneous PIV images of a spanwise travelling wave in quiescent air are shown in figure 5a,b through velocity magnitude and vorticity, respectively. In each part of figure 5, there are four images taken at the end of each of the four phases (i)–(iv) (figure 3). The location of the plasma actuators and the direction of the DBD plasma jets are indicated under each image. The travelling-wave direction is from left to right. On actuation of DBD plasma, a starting vortex is created [39], which develops and moves along and away from the wall in the positive z-direction as seen in phase (i). The core of the starting vortex is located at $y \approx 10 \text{mm}$ ($y^+ \approx 50$). The secondary vorticity is generated owing to the no-slip boundary condition [40], which is seen wrapped around the primary roller, aiding vortex movement away from the wall [41]. Phase (ii) shows the creation of a new starting vortex. This entrains the previously formed starting vortex generated in phase (i) to cause the two co-rotating vortices to coalesce, thrusting the fluid further in the spanwise direction. At the end of phase (iii), the wall jet begins to separate from the wall and wrap up around the starting vortex. The travelling wave appears to move the fluid effectively in the spanwise direction by entraining the high-speed fluid and adding momentum at each phase of forcing [42].

(b) Modification to turbulent boundary layers

The mean velocity and turbulence intensity are plotted across the boundary layer with and without spanwise oscillating plasma in figure 6. The plasma has caused a large reduction in mean velocity for $y^+ < 200$, owing to the creation of oscillatory streamwise vortices similar to those observed in the flow visualizations in figure 4. The phase-averaged spanwise velocity in the turbulent boundary
layer within a cycle of the plasma oscillation is shown in figure 7a. Plasma was created with force in the positive z-direction at $t/T_p = 0$ and with force in the negative z-direction at $t/T_p = \pi$ when the plasma pulse duration is $t_p^+ / T_p^+ = \pi/10$. Figure 7a demonstrates that the plasma successfully created a spanwise oscillation in the near-wall region of the turbulent boundary layer, with a maximum velocity of $\langle w_{\text{max}} \rangle^+ = 0.7$ at $y^+ \approx 15$, where triangular brackets denote phase-averaging. Within this spanwise oscillation region of $y^+ < 30$, $u^+$ is reduced.
by up to 36 per cent (figure 6b), which is accompanied by an increase in $v^+$ and $w^+$ of 100 and 20 per cent, respectively [44]. Figure 7a also shows that the plasma creates spanwise wall jets with half-thickness, $\delta_{1/2}^+ = 25–30$. This is similar to the optimum penetration depth for spanwise wall oscillation [35], although the velocity magnitude here is slightly less. It should be noted that the actual spanwise velocity measured between the electrodes was greater than the phase-averaged velocity. Above the oscillation region (say $35 < y^+ < 200$), $u^+$ increases by up to 30 per cent, with maximum $u^+$ at $y^+ \approx 50$.

We should also note that the velocity profile by plasma forcing differs somewhat from spanwise wall oscillation [35] or Lorentz force oscillation [27,28]. With plasma, there is little phase shift in $w^+$ with $y^+$, and no reversal in flow direction relative to the plasma force. Furthermore, figure 7b shows the data of figure 7a scaled with the instantaneous maximum velocity, $\langle w_{\text{max}} \rangle$, and jet half-width, $\delta_{1/2}$. A good collapse of the data is observed, which closely follows the theoretical velocity profile of the laminar wall jet [43].

The change in the mean velocity of the turbulent boundary layer with travelling-wave excitation is shown in figure 8a. Here, the data have been phase averaged over four spanwise locations. Similar to the spanwise oscillation as shown in figure 6a, travelling-wave excitation led to a velocity deficit in the lower part of the logarithmic region. It can be seen that the turbulent boundary layer was modified up to $y^+ = 100$ with a reduction in velocity spanning from $y^+ = 25–100$ by 10 per cent. We have shown in figure 5 that the starting vortices were generated on the initiation of DBD plasma, whose core was located at $y \approx 10$ mm ($y^+ \approx 50$). It is thought that these vortices are responsible for the velocity increase in the near-wall region through the entrainment of high-speed fluid from the outer boundary layer. The velocity decrease in the logarithmic region is considered to be the result of an upwash of the low-speed fluid from the near-wall region. The phase-averaged turbulence intensity profile with the travelling wave shows two peaks at $y^+ \approx 5$ and $y^+ \approx 50$ in figure 8b. The turbulence intensity is increased over nearly the entire boundary-layer thickness except in the outer layer at $y^+ > 100$.
Figure 8. (a) Mean velocity and (b) turbulence intensity profile of the turbulent boundary layer with spanwise travelling-wave excitation by plasma. $\lambda^+ = 500$ and $T^+_p = 82$. Scaled with canonical $u_t$. Open circles, canonical data; filled circles, travelling wave; solid line, $U^+ = 5.85 \log_{10} y^+ + 5.56$.

Figure 9. PDF of $u$-component velocity fluctuations for spanwise oscillation at (a) $y^+ = 5$ and (b) $y^+ = 20$. Dashed line, canonical data; solid line, spanwise oscillation.

The probability density functions (PDFs) of the $u$-component velocity fluctuations by spanwise oscillation are shown in figure 9, where the fluctuations have been normalized by their own standard deviation. In the viscous sublayer (figure 9a), the PDF shows a slight positive skewing and narrowing, reflecting an increase in skewness and kurtosis. This behaviour has also been observed in other drag-reducing flows [45]. Within the spanwise oscillating region ($y^+ \approx 20$), the PDF of plasma-controlled flow is mirrored to the canonical case, as shown in figure 9b. This suggests that the velocity fluctuations have changed to more positive, spiky, excursions of fluid (i.e. modified sweep events). These are likely to be associated with the wallward induction motion of the plasma-induced streamwise vortices. Note that the magnitude of the fluctuations is reduced in this region, such that these turbulent events are less violent.

Phil. Trans. R. Soc. A (2011)
The time series of $u$-component velocity fluctuations at $y^+ = 5$ with and without travelling-wave excitation are shown in figure 10. When the travelling wave is applied, the positive velocity spikes with larger positive fluctuations became more evident. This increases the skewness and kurtosis of the velocity signal by 25 per cent, which is clearly demonstrated by the change in PDF in figure 10.

(c) Changes in turbulence structure

The variable-interval time-averaging (VITA) technique [46] has been used to study the modification to near-wall turbulence activities. The threshold parameter was set at $k = 1$ and discrimination was applied to ensemble sweep events only ($du/dt > 0$). Figure 11a shows that the plasma has reduced the duration of the sweep events within the viscous sublayer ($y^+ = 5$) by 35 per cent while simultaneously reducing their intensity by 20 per cent. Similar reductions in sweep intensity and duration were observed at $y^+ = 20$ (figure 11b), although at $y^+ = 60$ the burst intensity has been increased by 30 per cent (not shown) owing to the increased magnitude of velocity fluctuations in this region. Note that the event frequency increases significantly with spanwise flow oscillation by plasma so that the oscillation causes weaker sweep events to occur at higher frequencies, as if the spanwise oscillation causes these events to happen prematurely. These are qualitatively similar to the results of Choi [45] for drag-reduced flow over riblets. It was also reported that the duration and strength of sweep events are reduced by 78 and 64 per cent, respectively, over the spanwise oscillating wall.
Figure 11. VITA-detected sweep events with spanwise oscillation at (a) $y^+ = 5$ and (b) $y^+ = 20$. Scaled with canonical $u_t$. Dashed line, canonical data; solid line, spanwise oscillation.

Figure 12. VITA-detected sweep events with spanwise travelling waves at $y^+ = 5$. Scaled with canonical $u_t$. Dashed line, canonical data; solid line, travelling wave.

and their frequency was increased by more than a factor of 2 [35]. We expect that the observed reduction in sweep intensity may lead to a reduction in skin-friction drag.

Du et al. [47] showed in their DNS study that creating a spanwise travelling wave with a unidirectional forcing configuration can increase the skin-friction drag. This perhaps is exemplified in the VITA analysis of the travelling-wave data at $y^+ = 5$, as shown in figure 12. Here, we see that the intensity of the sweep events in the viscous sublayer has been increased, although there is a small reduction in the sweep duration. This may suggest that the starting vortices generated on the initiation of DBD plasma in the travelling-wave excitation could increase the skin-friction drag owing to the entrainment of high-speed fluid from the outer regions of the boundary layer.
Figure 13. Phase-averaged velocity vectors throughout the plasma spanwise oscillation cycle. Solid line at the base of the plot indicates timing and direction of plasma force.

Figure 14. Instantaneous velocity magnitude at \( y^+ = 5 \) (a) with spanwise travelling waves and (b) without control.

Figure 13 demonstrates the oscillatory flow structure during the spanwise oscillation by combining the spanwise and wall-normal phase-averaged velocity profiles, where the solid line at the base indicates the timing and direction of plasma force. The flow is angled in the \( y-z \) plane by around 15° towards the wall for \( 0 \leq t/T \leq \pi \), while the flow is directed approximately 30° away from the wall for \( \pi \leq t/T < 2\pi \) at the particular spanwise location we measured (figure 2). The vortical motions observed in figure 13 show a strong similarity to the flow visualization in quiescent air (figure 4); therefore, it is likely that surface plasma has produced a system of streamwise vortices as a part of the spanwise flow oscillation.

The instantaneous distribution of velocity magnitude at \( y^+ = 5 \) with spanwise travelling waves was obtained by PIV measurement and is given in figure 14. On application of a plasma excitation at \( z^+ = 350 \), the low-speed region is spread in...
the region of $0 < z^+ < 300$ and $400 < z^+ < 500$, as shown in figure 14a. However, there seems to be an increase in velocity at $300 < z^+ < 350$ as a result of the downwash of the high-speed fluid by the travelling vortices, which may have led to an increase in skin friction [47]. Figure 14a also shows that there is a strong turning of near-wall velocity, suggesting that the skin-friction vectors are twisted in the spanwise direction over the regions of plasma forcing. This is qualitatively similar to the DNS results of Zhao et al. [48], who obtained a skin-friction reduction of 30 per cent with a flexible wall in a turbulent channel flow.

4. Concluding remarks

Our results for spanwise oscillation suggest that the plasma can create alternating spanwise wall jets in the near-wall region. This will twist the quasi-streamwise vortices in the near-wall region, producing a negative spanwise vorticity and reducing the near-wall velocity gradient, similar to the boundary-layer control with spanwise wall oscillation [35]. This takes place within the viscous sublayer and in the buffer layer, disrupting turbulence-producing activities (i.e. sweep and ejection events). On the other hand, the spanwise travelling waves by plasma actuators create starting vortices in sequence, which move as a single vortex engulfing the neighbouring vortices from the previous phases. The travelling vortices carry the low-speed fluid in the near-wall region of the turbulent boundary layer, spreading it along the wall to form a wide low-speed ribbon [23]. At the same time, there appears to be a streamwise vortex system playing some role in plasma flow control. We believe that the plasma actuation gives rise to streamwise vortices because the plasma occurs in discrete regions in the spanwise direction. When embedded in the boundary layer, these vortices reduce the mean velocity in the buffer and lower log region; a similar trend that has also been observed from streamwise vortices created by a synthetic jet issuing from a yawed slit [49]. The contribution of these vortices on the skin-friction drag is not clear at present.

The present study was conducted in the turbulent boundary layer at a relatively low Reynolds number of $Re_\theta = 1000$, mainly because of the limitation in the authority of DBD plasma actuators and their design. With a better understanding of the drag-reduction mechanisms in plasma flow control, together with an improvement in plasma actuator performance and design, we hope to be able to carry out high Reynolds number tests in the near future. This should provide us with vital information on the scalability of the plasma actuators to aeronautical applications. In order to support the results presented here, we are also expending effort in directly measuring the drag reduction.

This work was supported by the EU FP6 framework programme AVERT, the Engineering and Physical Sciences Research Council and BAE Systems.

References


