Turbulent boundary-layer control with spanwise travelling waves

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Abstract. It has been demonstrated through numerical simulations using Lorentz forcing that spanwise travelling waves on turbulent wall flows can lead to a skin-friction drag reduction on the order of 30%. As an aeronautical application of this innovative flow control technique, we have investigated into the use of Dielectric-Barrier-Discharge (DBD) plasma actuators to generate spanwise travelling waves in air. The near-wall structures modified by the spanwise travelling waves were studied using the PIV technique in a wind tunnel, while the associated turbulence statistics were carefully documented using hot-wire anemometry. We observed the spreading of low-speed fluid by the spanwise travelling streamwise vortices, which seems to have greatly attenuated the turbulence production process. This is very much in line with the finding of DNS studies, where wide low-speed ribbons replaced the low-speed streaks.

1. Introduction

Despite decades of research, there is still an on-going debate over the self-sustaining mechanism of wall turbulence (Jiménez & Pinelli, 1999; Bernard et al., 1993; Chernyshenko & Baig, 2005; Adrian, 2007). However, it is well accepted that the turbulent boundary layer comprises “coherent motions” with the role of near-wall turbulence events —such as the sweeps and ejections— being undeniable in the production of turbulence. If we are to achieve successful turbulent boundary-layer control, it is important for us to understand the coherent motions within the turbulent boundary layer as it is these motions that we must target for elimination.

Du et al. (2002) achieved a skin-friction drag reduction of 30% using spanwise travelling technique created by a Lorentz force. The spanwise travelling wave was implemented in a turbulent channel flow and studied using Direct Numerical Simulation (DNS). The ideal travelling-wave forcing equation that was used in their simulations was,

\[ F_z = I e^{-\frac{y}{\Delta}} \sin \left( \frac{2\pi \lambda}{L} z - \frac{2\pi}{T} t \right), \]  

where \( F_z \), was the spanwise force that was imposed at the wall and \( I \), was the amplitude of the travelling wave. The travelling-wave force was maximum at the wall and decayed exponentially with respect to a penetration depth, \( \Delta \). The wavelength of the travelling wave was denoted by, \( \lambda \) and the time period by, \( T \). A skin-friction reduction was obtained by applying periods of \( T^+ = Tu^2/\nu = 25, 50 \) or 100 depending on the penetration depth and amplitude of the Lorentz force.
The Lorentz force is limited to a conducting medium, such as sea water. Therefore, to make this innovative flow control technique applicable to air flows, we have investigated into the use of creating spanwise travelling waves with Dielectric Barrier Discharge (DBD) plasma. DBD plasma actuators consist of an upper and lower electrode separated by a thin dielectric material, figure 1a. On application of several kilovolts of AC power at kilohertz frequency between these electrodes, local ionization takes place around the upper electrode and couples momentum to the flow (Enloe et al., 2004). It has been shown that on initiation of DBD plasma in quiescent air a starting vortex (Whalley & Choi, 2010a) is generated. This vortex rolls up and moves along and away from the surface with continual plasma forcing leading the formation of a laminar wall jet.

In this paper, we present an experimental study using hot-wire anemometry and Particle Image Velocimetry (PIV) of spanwise travelling waves generated in air with DBD plasma for skin-friction reduction inside the turbulent boundary layer. As DBD plasma is a surface based technique, it makes an ideal candidate for turbulent boundary-layer control with spanwise travelling-wave excitation.

2. Experimental Set-up

Turbulent boundary-layer measurements were conducted using a low-speed, closed-loop wind tunnel. The wind tunnel had a cross section of 508 x 508 mm². The turbulent boundary layer was developed over a 3 m long flat plate, which was fabricated from 20 mm thick polished MDF and had a super-elliptic leading edge and a trailing-edge flap. The flat plate was positioned in the upper section of the wind tunnel with a turbulent trip placed 100 mm downstream from the leading edge. Measurements were taken a further 2.3 m downstream from the trip where the turbulent boundary layer was fully developed. The free-stream velocity was set at $U_\infty = 1.7$ m/s, with turbulence intensity of 0.24%. The turbulent boundary-layer thickness was $\delta = 90$ mm and the viscous sublayer was 1 mm. The Reynolds number based on the friction velocity was $Re_\tau = 435$, the Reynolds number based on the momentum thickness was $Re_\theta = 1024$ and the shape factor was $H = 1.46$. The pressure gradient across the test section was nearly zero.

The plasma actuator sheets used in the spanwise travelling wave experiments were photochemically etched from a copper-clad Mylar sheet (250 µm thick, dielectric constant $\varepsilon = 3.1$). Each plasma actuator sheet consisted of 24 copper electrodes which were powered by a set of high voltage sinusoidal RF inputs. The upper and lower electrodes were 2.5 mm and 6 mm ($z^+ = zu_\tau/\nu = 13$ and 30) in width respectively and protruded by 17 µm ($y^+ = 0.09$) from
Figure 2: Schematic representation of 4-phase spanwise travelling waves generated with plasma. a) Unidirectional forcing and b) bidirectional forcing.

the wall (see figure 1b). Each actuator had an active length of 338 mm ($x^+ = 1690$). The plasma actuator sheets were used to generate 4-phase spanwise travelling waves with two different forcing configurations over 3 wavelengths of $\lambda = 100$ mm ($\lambda^+ = 500$). Unidirectional forcing actuated in one direction per phase and bidirectional forcing actuated in two opposing directions per phase with electrodes separated by 56 mm ($s^+ = 280$). Figure 2a,b shows schematic representations of the uni and bidirectional forcing configurations, respectively. For the data presented in this paper, the sinusoidal voltage input to the plasma power supplies was fixed at $E = 7 \text{ kV}_{\text{p-p}}$ at a frequency of $f = 25$ kHz and applied with a forcing period of $T = 208$ ms ($T^+ = 82$), requiring up to 12 plasma power supplies.

Flow diagnostics were made by constant temperature hot-wire anemometry and PIV. The hot-wire measurements of the streamwise velocity were taken with Dantec 55P15 probes. One probe was used to obtain the boundary-layer profile, whilst another probe was kept stationary in the free stream of the wind tunnel to monitor the free-stream velocity. Each probe was operated with an overheat ratio of 1.8 and calibrated in-situ. The ambient temperature drift during experiments was monitored using a LM35 Precision Temperature Sensor and the hot-wire data was compensated accordingly.

The velocity fields of the $x$-$z$ and $z$-$y$ planes in the turbulent boundary layer were obtained with a time-resolved PIV system from TSI. The 2D PIV in the $x$-$z$ plane were performed 1 mm ($y^+ = 5$) from the wall within the viscous sublayer. These measurements had a field of view of 100 mm x 100 mm ($x^+ = 500, z^+ = 500$) and were positioned such that $(x^+, z^+) = (250, 250)$ was the centre of the travelling-wave actuator sheet. The measurements in the $z$-$y$ plane of the turbulent boundary layer were performed using stereoscopic PIV. The stereoscopic PIV data had a field of view of 100 mm x 40 mm ($z^+ = 500, y^+ = 200$) and positioned such that $(z^+, y^+) = (250, 0)$ was the centre of the travelling-wave actuator sheet with $y^+ = 0$ being the location of the wall. With respect to the $x$-$z$ plane measurements, the $z$-$y$ plane measurements
Figure 3: Streamwise velocity measurements in the $x$-$z$ plane of the turbulent boundary layer at $y^+ = 5$ showing a) canonical data, b) uni-directional spanwise travelling-wave data at $\frac{1}{2}T^+$ and c) bi-directional spanwise travelling-wave data at $\frac{3}{4}T^+$. $\lambda^+ = 500$, $T^+ = 82$. Scaled with canonical $u_\tau$.

were taken at $x^+ = 200$. Data processing was performed using INSIGHT 3G software from TSI using a cross-correlation algorithm to generate vectors over a 32 x 32 pixel interrogation area with 50% overlap to an accuracy of $3-5\%$ (Westerweel, 1997).

3. Results and Discussion

The change in near-wall structure of the turbulent boundary layer in the $x$-$z$ plane at $y^+ = 5$ with spanwise travelling waves is shown in figure 3. The boundary-layer flow is in the positive $x-$direction and the spanwise travelling wave is moving in the positive $z-$direction. The near-wall streaky structure (no-control) can be seen in figure 3a, where the low- and high-speed streaks can be seen meandering through the flow with characteristic streak spacing of $z^+ = 100$. The application of spanwise travelling waves with uni and bidirectional excitations with period $T^+ = 82$ are shown in figure 3b and figure 3c, respectively. The spanwise travelling-wave data shown here have been phase-averaged over 51 forcing periods. Unidirectional forcing, figure 3b, has plasma forcing at $z^+ = 225$ (with actuators on the side of each image to show the location of plasma forcing). A wide ribbon of low-speed streamwise velocity is being pushed in the positive spanwise direction, $300 < z^+ < 400$, and $z^+ < 300$ has no clear sign of near-wall streaky structures due to plasma forcing of previous phases. Bidirectional forcing is shown in figure 3c, with plasma forcing at $z^+ = 50$ and $z^+ = 350$. Again, there is a large change in near-wall structure as compared to the no-control case, figure 3a. Here, collections of low-speed ribbons for $z^+ < 50$, $100 < z^+ < 300$ and $350 < z^+ < 500$ can be seen. This is a combination of the low-speed streamwise velocity collected during the current and previous phases of the travelling-wave excitation.

Stereoscopic PIV measurements in the $z$-$y$ plane of the turbulent boundary layer with spanwise travelling waves are shown in figure 4. In figure 4, the boundary-layer flow is moving into the plane of the paper and images are taken at a streamwise distance of $x^+ = 200$ in relation with the $x$-$z$ plane data. Figure 4a shows streamwise vorticity with unidirectional forcing (in the left column), where a co-rotating streamwise vortex can be seen by the strong negative vorticity with arrows of $V^-$ and $W^-$ components of velocity. The streamwise vortex generated during unidirectional forcing is entraining low-speed streamwise velocity from the near-wall region into the core of the streamwise vortex and around its periphery, figure 4b. The streamwise vortex is being thrust in the spanwise direction by the activated plasma actuator, which produces strong positive spanwise velocity along the wall, figure 4f. The positive spanwise velocity extends to a wall-normal distance of $y^+ = 50$, figure 4c and due to induction by the streamwise vortex, negative spanwise velocity is seen above the vortex core, $50 < y^+ < 100$. The streamwise vortex
Figure 4: Phase-averaged data in the z-y and x-z planes of the turbulent boundary layer with spanwise travelling-wave excitation by plasma with unidirectional forcing at $\frac{1}{2} T^+$ (left column) and with bidirectional forcing at $\frac{3}{2} T^+$ (right column). a) Streamwise vorticity (y-z plane), b) streamwise velocity (y-z plane), c) spanwise velocity (y-z plane), d) wall-normal velocity (x-z plane), e) streamwise velocity (x-z plane) and f) spanwise velocity (x-z plane). $\lambda^+ = 500$, $T^+ = 82$. Scaled with canonical $u_\tau$. 
creates both upwash and downwash, figure 4d, with the region of downwash coinciding with the location of the plasma actuator and a region of high-speed streamwise velocity in the near-wall region, figure 4e. The location of the wide ribbon of low-speed fluid, figure 4e, coincides with the location of the streamwise vortex, figure 4a. Hence, the streamwise vortex that is travelling in the spanwise direction is effectively spreading the near-wall streaks into wide ribbons of low-speed fluid.

Figure 4a shows streamwise vorticity with bidirectional forcing (in the right column), where co- and counter-rotating streamwise vortices can be seen by the strong negative and positive vorticity. Both co- and counter-rotating vortices are created with bidirectional forcing as the plasma actuators fire in two opposing directions each phase. As has been seen with unidirectional forcing, the streamwise vortices generated during bidirectional forcing are entraining low-speed streamwise velocity from the near-wall region into the streamwise vortex cores and around their peripheries, figure 4b. The streamwise vortices are being thrust in both the positive and negative spanwise direction by the activated plasma actuators, which produces both strong positive and negative spanwise velocity along the wall, figure 4f, that extends to a wall-normal distance of $y^+ = 50$, figure 4c. Again, as was found with unidirectional forcing, the streamwise vortices generated with bidirectional forcing create spanwise velocity for $50 < y^+ < 100$ due to induction, along with positive and negative wall-normal velocity, figure 4d, which coincides with regions of high-speed streamwise velocity in the near-wall region, figure 4e. Furthermore, the location of the wide ribbons of low-speed fluid, figure 4e, coincide with the locations of the streamwise vortices, figure 4a.

Streamwise velocity profiles, which have been phase-averaged over four spanwise locations with spanwise travelling-wave excitations are shown in figure 5. Both the uni and bidirectional travelling waves yield a large reduction in streamwise velocity in the logarithmic region of the turbulent boundary layer of 10% and 20%, respectively, typically up to a wall-normal distance of $y^+ = 200$. The reduction in streamwise velocity is due to the upwash of low-speed streamwise velocity from the viscous sublayer by the streamwise vortices, as shown in figure 4b. At the same time, the spanwise travelling waves cause an increase in the streamwise velocity in the near-wall region, $y^+ < 20$, due to the downwash associated with the plasma actuators, figure 4d.

We have previously demonstrated (Choi et al., 2011) that the unidirectional travelling wave creates streamwise vortices in sequence, which move as a single vortex engulfing the neighbouring vortices from previous phases. The bidirectional travelling wave activates plasma
in two opposite directions per phase, causing a complex interaction of co- and counter-rotating streamwise vortices that lift one another away from the wall to maintain the travelling-wave excitation (Whalley & Choi, 2010b). Both forcing configurations generate a streamwise vortex, as demonstrated in figure 4a, that travels in the spanwise direction. It is thought that the streamwise vortex which is travelling in the spanwise direction is spreading the low-speed fluid within the viscous sublayer, creating wide ribbons of low-speed fluid. This result is in line with DNS studies (Du et al., 2002) and it is conjectured that the spanwise travelling waves are stabilising the near-wall streaky structure, leading to a reduction in turbulent skin-friction.

4. Conclusions

Our results have shown that spanwise travelling waves with uni and bidirectional forcing configurations can be implemented in air with DBD plasma inside the turbulent boundary layer. The unidirectional travelling wave creates streamwise vortices in sequence, which move as a single vortex, engulfing the neighbouring vortices from previous phases. The bidirectional travelling wave activates plasma in two opposite directions per phase, causing complex interactions between co- and counter-rotating streamwise vortices. It has been seen that both forcing configurations generate streamwise vortices that spread the low-speed fluid within the viscous sublayer, creating wide ribbons of low-speed fluid. This result is in line with DNS studies (Du et al., 2002) and it is conjectured that the spanwise travelling waves implemented with DBD plasma are stabilising the sublayer streaks and have the potential to realise large reductions in skin-friction drag.

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