PROPORTIONAL OPPOSITION CONTROL OF TURBULENCE

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Abstract

Proportional opposition control of sweep events in a turbulent boundary layer has been carried out using a wall-normal jet. Changes to the turbulence structure in the region closer to the wall have been examined using hot-wire anemometry. Control of each detected sweep event has been obtained by using multiple injections whose number is proportional to the duration of the event. Differently from the more conventional opposition control technique with a single injection of a longer duration, the proposed technique with multiple injections allows to control the sweep event over its whole duration without changing the working parameters of the jet actuator.

1 Introduction

During last decade, many attempts have been done to control turbulence in wall bounded flows. In particular recent studies have shown that near-wall turbulence events can be manipulated by means of a relatively simple control scheme, leading to skin-friction reductions. Choi *et al* [1] performed direct numerical simulations of active control in a turbulent channel flow and showed that using blowing and suction in opposition to the wall-normal velocities produced by bursting events close to the wall, skin friction reduction up to 25% can be achieved. They also found that when the detection plane is located close to the wall ($y^+\approx10$) drag is reduced, but when the detection plane is located further from the wall, drag dramatically increases.

Hammond *et al* [2] pointed out that the opposition control establishes a "virtual wall", halfway between the detection plane and the physical wall. Being no flow through the virtual wall, the downwash of high momentum fluid towards the wall can be prevented producing an effective skin-friction drag reduction.

Rebbeck and Choi [3] experimentally investigated how the near-wall turbulence structure of the boundary layer is modified when opposition control is conducted on the individual sweep events with a wall-normal jet from a piston-type actuator. They also pointed out that the turbulent skin-friction drag can be reduced by selectively canceling the downwash of higher-speed fluid during the sweep events. In this experiment the effect of opposition control of near-wall turbulence has been observed using a particular technique and without carrying out real-time control: a piston type actuator was operated at a fixed cycle to issue wall-normal jets from the wall and the velocity signals from the hot-wire sensors were continuously sampled. Velocity data were successively analyzed off line to obtain an ensemble-averaged burst signature of the sweep events when they are opposed by a wall-normal jet. More recently the same Authors [4] carried out a wind-tunnel experiment on opposition control in real-time. The results showed that the wall-ward movement of high-speed fluid during the sweep event can be successfully blocked by the wall-normal jet produced by a loudspeaker actuator, suggesting that the skin-friction drag of the turbulent boundary layer can be reduced by opposition control of wall turbulence.

Rathnasingham and Breuer [5] showed how the effectiveness of the opposition control in practical applications can be improved using wall-normal jets issuing from a long streamwise slit instead of circular jets. In this way the

streamwise coverage of the opposition control is increased and the sweep events can be blocked for a longer streamwise distance.
In the present study control of each detected sweep event has been obtained by using multiple injections whose number is proportional to the duration of the event. Modifications of the near-wall turbulence structure in the boundary layer produced by this control strategy are shown in the following.

2 Experimental set-up

Experiments were carried out in a open loop wind tunnel, with 500mm high and 700mm wide test section. Measurements were taken over a flat plate 3400mm long, spanning the whole test section. A trip device, consisting of a two-dimensional array of cylindrical studs, was positioned at 100mm from the leading edge of the flat plate. The diameter and the height of the cylindrical studs were equal to 4mm and 8mm respectively, while their spacing in the streamwise and spanwise direction was equal to 12mm. The Reynolds number based on the height of studs and the freestream velocity was 2760. The natural boundary layer at the controlling section located 1900mm from the leading edge was characterized by a Reynolds number based on the momentum thickness $Re_\theta \approx 2000$ and a shape factor H=1.34 . The obtained mean velocity profile and the higher turbulence statistics of the fluctuating longitudinal velocity component show profiles typical of a fully developed turbulent boundary layer.
Two hot-wire probes were used in the present experiment. Each probe was connected to a Dantec 55M10 CTA Standard Bridge. The first probe (figure 1), positioned upstream the orifice (x^+=-110) and used to detect the sweep events, is a Dantec 55P11 straight probe with a sensitive tungsten wire of 5μm in diameter and 1.25mm long. The sweep events have been detected by using the velocity gradient technique applied to the longitudinal component of the velocity *u* measured by this probe. More precisely the gradient technique has been applied to the analog voltage output from the anemometer driving the front probe. When the voltage gradient exceeds a given threshold a sweep event is detected. In the present study only the control of the strong sweep events has been carried out thus reducing the probabilities of false detections made by the velocity gradient technique (see [4]). The sweep detection was carried out in real time by means of an analogue differentiating device and a comparator device. When a sweep event is detected, a TTL signal is sent to a signal generator to activate a loudspeaker actuator. This actuator is able to produce multiple injections (through a circular orifice with a diameter equal to 1mm) whose number is proportional to the time over which the gradient is above the threshold. An actuation frequency *f*=325Hz has been selected. This frequency is high enough to allow multiple injections during the sweep event duration. Proportional control of sweep events is also possible by adjusting the strength of the wall-normal jet according to the gradient of the detected velocity signal, as suggested by Rebbeck an Choi [4], or by using wall-normal jets with a variable duration, thus changing the streamwise coverage of the opposition control. However, the author believes that the strategy based on multiple injections presented in this paper is able to guarantee an efficient control of sweep events under a wide range of fluid conditions without requiring a significant change of the working parameters of the actuator. In particular this strategy seems to be suitable for practical applications where the Reynolds number of the main flow can vary.
The second probe, positioned at different streamwise positions downstream the orifice and used to observe the turbulence structure modifications produced by the opposition control in the region closer to the wall, was a Dantec 55P15 boundary-layer probe with a sensitive tungsten wire of 5μm in diameter and 1.25mm long (corresponding to 19 wall units). Both probes were calibrated in situ and the calibration curves were fitted with the King's law. Data were collected by a National Instruments PCI-MIO-16-XE-10 16-bit DAQ board. Velocity time histories consisted of 2^{20} data points each and were sampled at 12 kHz.

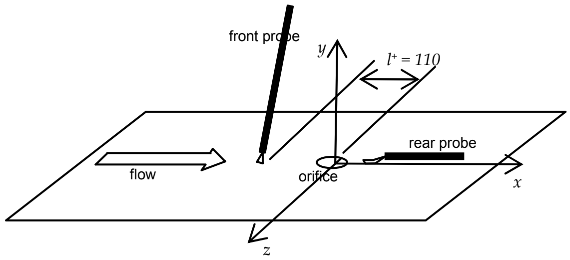
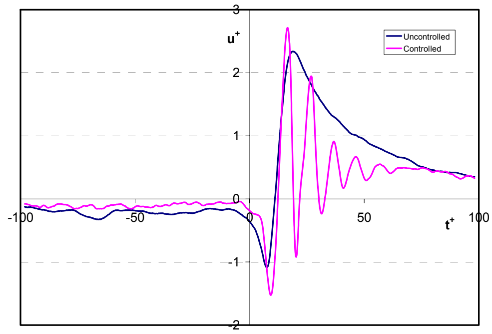


Fig. 1 Sketch of the experimental set-up and reference system.

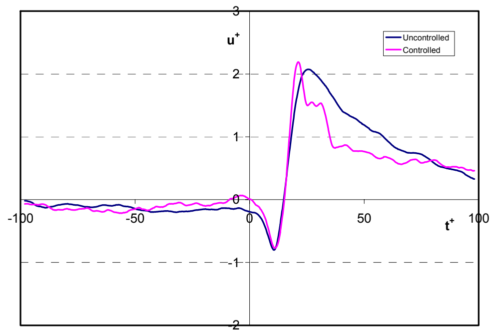
3 Results

Measurements at different streamwise locations were performed in order to characterize the modifications in the flow behavior when the control is active. Figures 2a and 2b show the conditional averaged sweep signature at two different streamwise locations (x^+=30 and x^+=77 respectively) and for a wall normal distance y^+=12. The sweep detection is made at t^+=0. Figure 2a shows modifications made to the sweep event by the wall-normal jet at x^+=30 downstream the actuator. Strong velocity oscillations appear in the sweep signature due to the intermittent nature of the actuation. It is clearly visible how the repeated injection is able to control the event over its whole duration producing reductions of the longitudinal velocity component with a frequency corresponding to the actuation frequency of the wall-normal jet. At further distance (x^+=77) from the actuator (figure 2b) the oscillations previously observed are strongly attenuated and for t^+>20 a consistent reduction of u velocity component is clearly visible.

As pointed out by Rebbeck and Choi [4], the opposition control of wall turbulence carried out by means of wall-normal jets acts as a combination of in-phase u-velocity and out-of-phase v-velocity control. When the wall-normal jet is issued from the orifice, a low speed region is created near the wall, thus providing the in-phase u-velocity control. The vertical velocity of the wall-normal jet is equal in magnitude but opposite in direction to that of the sweep event. In this way the out-of-phase v control blocks the wall-ward advancement of the sweep event.



a)



b)

Fig. 2 Conditional averaged sweep event at y^+=12, a) at x^+=30 downstream the actuator; b) at x^+=77.

Figure 3a shows the percentage variations of the mean velocity for different streamwise locations and y^+=12. For a distances between x^+=30 and x^+=100 from the jet orifice appreciable reductions (up to about 8% for x^+=30) are observable. This behavior can be related to formation of a pair of counter-rotating vortices with a common up-flow produced as a result of the interaction between the wall-normal jet and the boundary layer [4]. These counter-rotating vortices produce a central well of low-speed fluid with high-speed regions on either side. Moving downstream, between x^+=100 and x^+=300, an increase up to about 3% of mean velocities can be observed. This effect can be probably due to the fact that the interaction between the wall-normal jet and the boundary layer produces a bending of the jet column in the streamwise direction. This results in an increase of the longitudinal momentum for a certain range of distances from the orifice. Fig. 3b shows the percentage variations of the velocity fluctuations. An increase, up to about

4%, can be observed in the region closer to the jet. These higher values of fluctuations are due to the strong oscillations produced by the repeated injection used to control the sweep events as evidenced in figure 2a. For higher distances from the injection point an appreciable decrease in fluctuations is present. These reductions are still observable at x^+=450 , indicating that the control counteracts the near-wall turbulent activity with long-lasting effects.

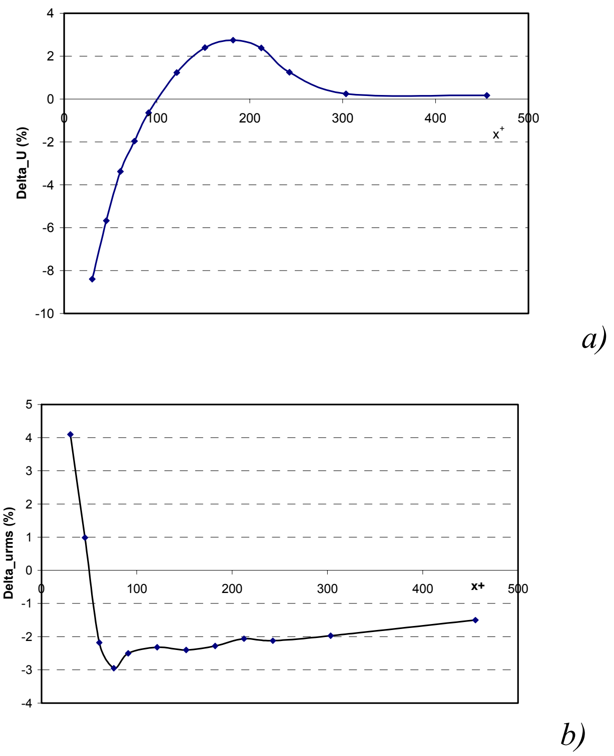


Fig. 3: a) Percentage variations of longitudinal mean velocity component, b) Percentage variations of longitudinal velocity fluctuations. y^+=12.

In order to get more information on the structure modifications produced by the control, the autocorrelation function, R_{uu}, of the streamwise fluctuating velocity measured at y^+=12 and for different distances from the injection point, is shown, for the natural and the controlled flows in figure 4. The autocorrelation function computed at a streamwise distance x^+=30 (figure 4a) clearly shows that the longitudinal integral scale is significantly reduced in the controlled flow, indicating that the streaky structure is fragmented and weakened by the action of the wall-normal jet. The presence of relative maxima for τ^+≈11 and its multiple is related to the frequency (*f*=325Hz) of repeated injections operated during the control of a sweep event. The autocorrelation function computed at x^+=77 (figure 4b) also shows a consistent reduction of the longitudinal integral scale, but the presence of secondary peaks is not evident. At x^+=310 (figure 4c) the differences between the natural and the controlled case are not appreciable.

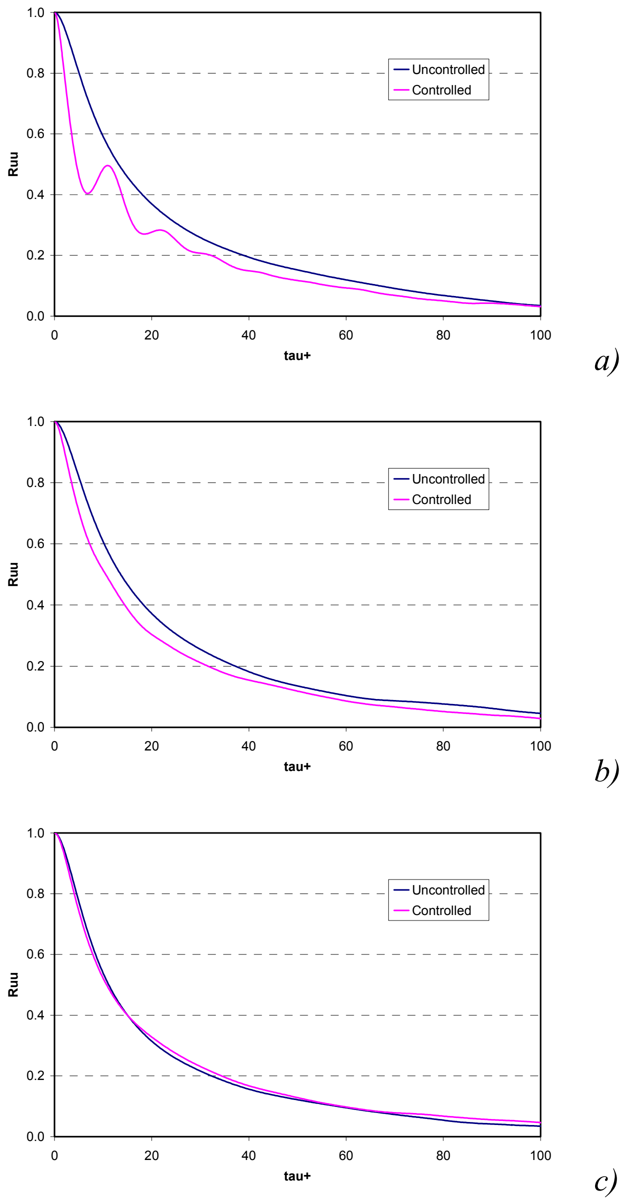


Fig. 4: Autocorrelation function R_{uu} computed at a) x^+=30, b) x^+=77, c) x^+=310. y^+=12.

4 Conclusions

In the present study control of sweep events has been obtained by using multiple injections whose number is proportional to the time over which the gradient of the detected velocity signal is above the threshold. The proposed technique with multiple injections allows to control the sweep event over its whole duration without changing the actuation parameters. In the region close to the wall and for distances between $x^+=30$ and $x^+=100$ from the jet orifice, consistent reductions (up to 8%) are observable in the mean velocity distribution, suggesting the possibility of reducing the skin-friction drag of the turbulent boundary layer by means of this control technique. For higher distances from the injection point a consistent decrease in fluctuations is present, indicating that the opposition control operated with multiple injections has long-lasting effects on the near-wall turbulent activity. Moreover, the autocorrelation function of the streamwise fluctuating velocity computed for $y^+=12$ and different distances from the injection point, shows a reduction of the longitudinal integral scale when the control is activated.

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