CONTROL OF TURBULENT DRAG BY LOCALIZED BLOWING PERIODICAL AND DISSYMETRIC IN TIME

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ABSTRACT

Experimental results on the reaction of the near wall turbulence and drag to a localized time periodical blowing are reported. The injection velocity is periodical and dissymmetric in time, with a rapid acceleration phase followed by a slow deceleration one. The flow is relaminarized during 70% of the oscillation period mainly during the deceleration phase. The latter maintains stable the vorticity layer induced by the blowing and prevents its roll-up contrarily to a sinusoidal-time periodical blowing. Thus, a time mean drag reduction of 55 % is obtained at 100 wall units downstream of the blowing slot and this is 37% larger than the drag reduction obtained by a steady blowing with the same time mean severity parameter. Direct numerical simulations results confirm these observations, in particular the near wall activity is considerably reduced in the case of local blowing periodical and dissymmetric in time.

INTRODUCTION

Intensive direct numerical simulation investigations conducted during the last decade have clearly shown that the optimal and suboptimal control of the near wall turbulence are plausible and that appreciable drag reduction of about 30-40 % can be achieved through either adaptive or non adaptive schemes. The literature on this topic is vast now and the reader may consult Bewley et al. (2001, 2004) for some recent ideas and developments. The suboptimal control consists of minimizing the wall shear in time and space through pinpoint blowing and suction at the wall. The formulation of the control strategy is easily achieved by the introduction of the adjoint problem and the blowing/suction distribution is monitored according to the adjoint pressure by steepest gradient method. The major shortcoming of these methods is the necessity of a dense distribution of sensors (wall shear stress gauges) and actuators (micro blowing-suction jets) with a mesh size roughly equal to the viscous sublayer thickness to achieve significant drag reduction. Increasing the control mesh size decreases the efficiency of the control scheme. This not always well understood at a first glance. Indeed, the streamwise and spanwise scales of the coherent eddies near the wall are at least an order of magnitude larger than the required control space step. The quasi-streamwise vortices present in the buffer layer are about 300-500 wall units long and are separated by 100 wall units in the spanwise direction. They generate turbulent wall shear by stretching spanwise vorticity zones through ejections and sweeps. However their regeneration and locations are random in time and space and their capture and subsequent control decision require significantly smaller time and space scales. This poses technical feasibility problems of the sub-optimal strategies, despite the important progress achieved in micro-smart technologies nowadays. Suction, on the other hand, is undesired in practical applications. Investigations of somewhat simpler large-scale control methods are therefore still necessary.

One of the ways to remedy to the shortcomings discussed above is to make use of dual-control. The latter consists of exciting a system to increase its predictability and its controlability as a consequence. We applied this strategy by making use of a localized blowing sinusoidal in time with a small severity parameter in Tardu (2001). We found an unexpectedly strong effect on the near wall turbulence especially in the high frequency regime. The local blowing induces a vorticity layer that is of opposite sign of the underlying base flow. The easiest way to explain this phenomenon is to notice that, basically the blowing acts in an opposite way to the suction. The latter suppresses the existing vorticity that is replaced to maintain the non-slip condition. Near the wall the major vorticity component is in the spanwise direction. It is moreover negative at the mean $\overline{\Omega}_z < 0$ and its instantaneous fluctuating part ω_z is skewed towards the negative values (the skewnesss of ω_z is -1 at the wall). Therefore the suction induces a negative spanwise vorticity layer and the local blowing a positive one. The physical mechanism governing the blowing is of course not simply the opposite of suction and more convincing arguments can be found in Tardu (2001). The induced vorticity layer advects and diffuses from the wall. In the case of sinusoidal time periodical blowing, however, the diffusion is constrained into a layer of thickness $\propto^{+} \propto \frac{1}{\sqrt{f^{+}}}$. Hereafter $^{+}$ denotes the quantities in wall units, non-dimensionalized by the shear velocity and the viscosity. The vorticity layer can hardly be affected by the turbulent mixing when δ^{+} is smaller than the low buffer layer thickness $\delta^{+} < 10$. It concentrates and becomes compact under these circumstances. Its first effect is to dilute the prevailing negative vorticity layer near the blowing slot. The flow is consequently partly relaminarized during the acceleration phase of the injection velocity $< v_0 >$. The relaminarized phase is unstable and inflexional points appear in the phase averaged velocity during the deceleration phase. This is one of the main characteristics of the relaminarization process whose stability is difficult to be maintained. A time mean drag reduction of about 60% is obtained in near the blowing slot until a streamwise distance of about $x^{+} = 50$

wall units downstream while the drag reduction by steady blowing with the same mean severity parameter is only 40 %. After $x^+ > 50$, however, the reaction of the near wall turbulence changes somewhat abruptly. Due, on one hand, to the destabilization of the near wall flow in the $\frac{\partial < v_0 >}{\partial t} < 0$ phase, and, on the other, to the constrained diffusion, the induced positive spanwise vorticity rolls up into a coherent vortex. The letter increases the drag in a predictable fashion as it is convected downstream. The system results in a drag penalty for $x^+ > 50$, and can be used in separation rather than in drag control. The induced positive vorticity layer, its destabilization in the relaminarization phase, its roll-up due to the concentration and vorticity discontinuities and, finally the increase of the wall shear stress as the coherent vortex is convected downstream are schematically shown on this Figure. More details are available in Tardu (2001).

AIM OF THE PRESENT INVESTIGATION

The absolute values $\left|\frac{\partial < v_0 >}{\partial t}\right|$ of the time acceleration and deceleration are sensibly equal in the case of sinusoidal time periodical injection velocity. Our previous observations recapitulated above indicate that the time acceleration/deceleration play a fundamental role in the reaction of the turbulent drag. The present investigation is based on a simple idea, namely that time/space acceleration stabilizes and the deceleration destabilizes the flow. It is therefore, asked whether, a localized blowing, periodical but dissymmetric in time with a rapid $\frac{\partial < v_0 >}{\partial t} > 0$ followed by a slow $\frac{\partial < v_0 >}{\partial t} < 0$ phase can prevent the roll-up of the induced vorticity layer and the resulting drag penalty observed with sinusoidal injection velocity. An important aspect that consequently rises is to determine how sensitive is the reaction of the turbulent wall shear stress to the temporal variation of the injection velocity. The answer to this question will clarify whether an optimal temporal waveform of the localized blowing exists or not. This will give more insight to the physics of the near wall turbulence control and will allow the development of new suboptimal control strategies as well.

DEFINITIONS, EXPERIMENTAL SET-UP AND DATA REDUCTION

An experimental model has been developed in the low-speed wind tunnel of our laboratory. The blowing and suction at the wall are done through spanwise slots of dimensions 0.6*100 mm corresponding to 10*1667 in wall units in the present working conditions. Two special pulsating devices have been designed for the present purpose. The first one provides sinusoidal oscillating blowing and has been described in Tardu (2001). The second, new one consists of a profiling cam-valve that rapidly opens the slot and covers it slowly in time. A Brooks flow-meter is used to regulate the flow rate accurately.

The wall shear stress measurements have been performed by means of a Cousteix-Houdeville wall hot-wire gauge (HWG) to avoid problems caused by the conduction into the substrate. Nice results have been obtained up to the statistics of order 4 and the details may be found in Tardu (1998, 2001).

In order to extract the deterministic and deduce the undeterministic part of the flow quantities the classical triple decomposition is used. A flow quantity $q(\vec{x},t;T)$ is decomposed into a time mean $\bar{q}$ an oscillating $\tilde{q}$ and a fluctuating q' part, where T stands for the period of the oscillating blowing. The phase average is denoted by $< q >= \bar{q} + \tilde{q}$. The modulation characteristics have been determined through a least square Fourier analysis.

In flows with local blowing/suction the severity parameter is defined as the ratio of the injection or suction flow to the *incoming* flow rate, i.e., $\int = \frac{v_0 L_x}{\int_0^{\delta} \bar{u}\, dy}$ (Tardu, 1998). The injection velocity in steady blowing experiments investigated here is $\bar{v}_0 = 1 m/s$ and the severity parameter is only $\Theta = 0.006$. The shape parameter just downstream of the slit at $\frac{x}{\delta} = 0.1$ is $H = 1.4$ under these circumstances. In unsteady blowing experiments, the injection velocity $< v_0 >$ changes in a cyclic manner between 0 and 2 m/s. The maximum value of the severity parameter in the oscillation cycle is therefore $\Theta = 0.012$ and $H = 1.7$ which is still below the limit of flows prone to separate. Note, by the way, that in DNS studies dealing with active control conducted so far, the severity parameter is zero, because of the pinpoint intervention. In practical situations this is impossible, and even a low Θ may affect profoundly the flow in the neighborhood of the injection/suction region. This may be an additional point to consider the DNS results with some caution.

EXPERIMENTAL RESULTS

Fig. 1 shows the phase average of the injection velocity $< v_0 >$ corresponding to the sinusoidal (S) and dissymmetrical (D) localized blowing. The imposed period is $T = 28 ms$ and that corresponds to an imposed frequency of $f^+ = 0.0134$ in wall units. The sinusoidal injection velocity $< v_0 >$ compares well with the first harmonic deduced from a Fourier analysis. The deceleration of the D blowing is approximately 0.4 times milder than the sinusoidal blowing although the acceleration phases are roughly comparable in both cases. The dissymmetrical blowing presents consequently higher harmonics with the amplitude of the second harmonic being as large as $\frac{1}{4}$ times the first.

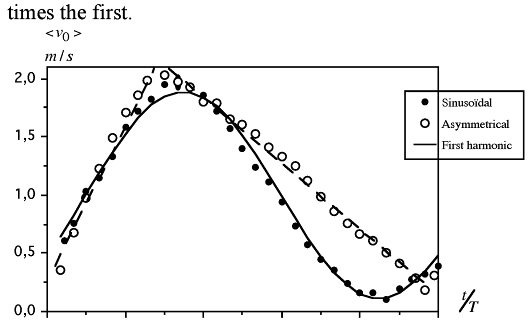


Figure 3 Phase average of the injection velocity in the case of sinusoidal and dissymmetric blowing. The sinusoidal blowing injection velocity phase average

compares well with the first harmonic resulting from a discrete Fourier analysis. The imposed period is 28 ms.

Fig. 2 compares the phase average of the wall shear scaled with the local mean shear stress $\overline{\tau}_{SBL}$ of the standard unmanipulated boundary layer resulting respectively from the S and D blowing at $x^+ = 112$ downstream of the slot. Recall that both D and S managements are performed in situ under the same conditions and at the same location. The strong local peak in the wall shear stress at $t/T = 0.4$ under the sinusoidal injection is caused by the roll-up mechanism summarized in the Introduction. Both the location and magnitude of this peak, and even the entire phase average $<\tau>$ compare well with our previous measurements (Tardu, 2001) despite the fact that the present investigation is entirely independent. That is a clear proof of the repeatability of the measures.

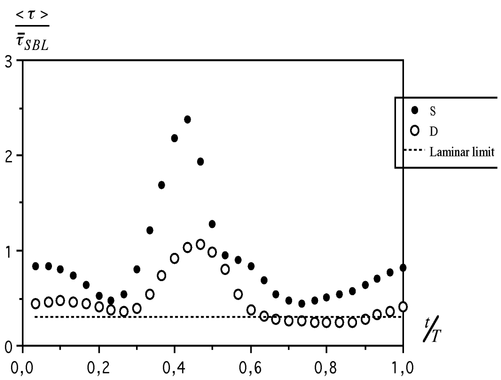


Figure 2 Phase average of the wall shear stress in the case of S and D blowing. The imposed frequency in wall units is $f^+ = 0.0134$. The amplitude and the time mean of the injection velocity are 5 wall units.

The reaction of the turbulence is strongly different under the influence of the D blowing. The flow is relaminarized during 70% of the oscillation cycle, especially during the decelerating phase of $< v_0 >$. The ratio of the mean shear stresses in the D and S cases is as small as $\frac{\overline{\tau}_D}{\overline{\tau}_S} = 0.50$ indicating that the dissymmetric blowing is twice more efficient in terms of drag reduction. There is a local maximum in $<\tau>$ at $t/T \approx 0.5$ that hardly reaches the shear stress of the standard boundary layer. That might be due to either the inherent response of the near wall turbulence or to a weak spanwise vortex resulting from a mechanism similar to the S blowing. The second hypothesis is presumably unlikely. Indeed, the convection of the induced spanwise vortex is generally associated with high wall shear stress intensity that is well localized in time as it can be seen in Fig. 3.

The local maximum of $<\tau\tau\tau>$ is clear and is as large as $3\overline{\tau\tau\tau}_{SBL}$ in the S case. The time-asymmetry in the injection velocity suppresses almost entirely the turbulence activity during the deceleration phase. The $<\tau\tau\tau>$ peak value on the other hand is not as clearly discernible as it is in the S case.

The phase averages of the skewness $< S > = \frac{<\tau\tau^3>}{<\tau\tau^2>^{3/2}}$ and flatness $< F > = \frac{<\tau\tau^4>}{<\tau\tau^2>^2}$ of the fluctuating wall shear stress at $x^+ = 112$ are shown respectively in Fig. 4 and 5.

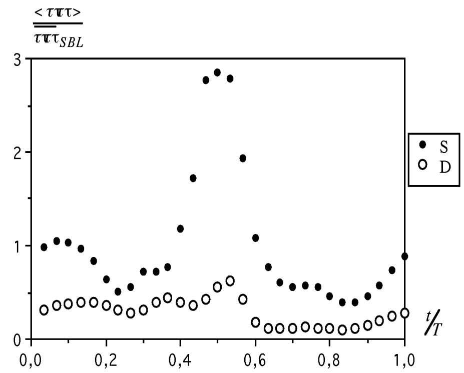


Figure 3 Phase average of the wall shear stress turbulent intensity in the case of S and D blowing. See the legend of Fig.2 the for the experimental conditions.

The phase averages are well converged thanks to particularly long time series analyzed here. Global is the strong non-linear response of the fine structure of the turbulence to imposed localized time blowing. The most impressive feature of Fig. 5 is the occurrence of a very high τ' intermittency in the case of D blowing. The flatness reaches cyclically values as large as 30, which is approximately 8 times larger than the standard boundary layer value $F = 4$. The high intermittency takes place mainly at the middle of the relaminarized phase. The time mean flatness factors are respectively 7.5 and 15 in the S and D cases. The skewness cyclic variation is roughly similar in the S and D cases. Note that $< S >$ is significantly larger than its standard boundary layer value ($S = 1$). That might be explained by the weakening of the ejection events and of their impacts near the wall.

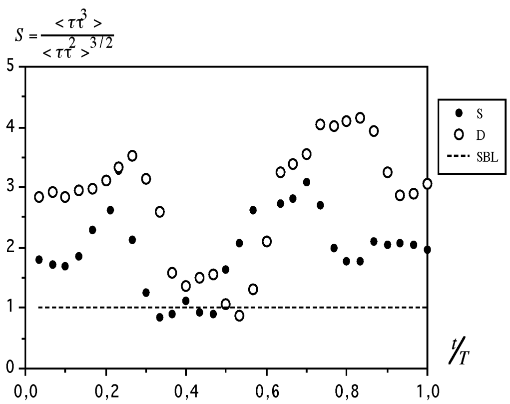


Figure 4 Phase average of the skewness of the wall shear stress turbulent intensity in the case of S and D blowing. SBL refers to the Standard Boundary Layer.

DIRECT NUMERICAL SIMULATIONS

The DNS code developed by Orlandi (2002) hasbeen modified and adapted to investigate the effect of localized blowing of different temporal shapes. The code is of finite difference type combined with fractional time procedure. The non-linear terms are explicitly resolved by an Adams-Bash forth scheme. Periodical boundary conditions are used in the homogeneous streamwise and spanwise directions. The size of the computational domain is $(4\times \times 2\times 1.33\times)$ in respectively the streamwise x, wall normal y and spanwise z directions. The flow parameters are non-dimensionalised with respect to the channel half width and the centerline velocity. There are $(513\times 219\times 219)$ computational modes in (x,y,z). The Reynolds number is fixed at $Re = 4200$.

The sinusoidal and dissymmetric localized blowing are studied simultaneously beginning with the same initial conditions to alleviate direct comparison. The results presented here have been obtained after 30 000 iteration steps representing 40 imposed time period while the imposed frequency is exactly identical to the experiments.

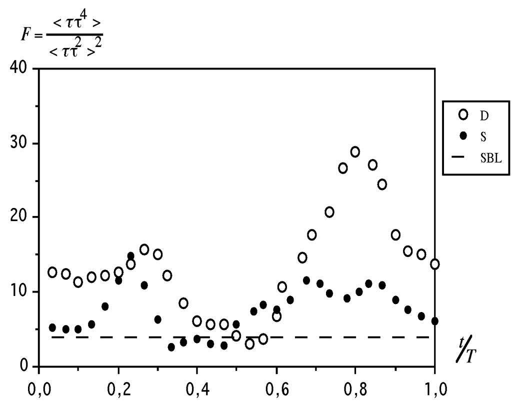


Figure 5 Phase average of the flatness of the wall shear stress turbulent intensity in the case of S and D blowing. SBL refers to the Standard Boundary Layer.

Fig. 6 compares the wall shear stress distribution in the (x^+,z^+) plane in the case of S and D blowing at $t/T = 0.5$. The mean flow direction is from left to right. The shear is non dimensionalized with $\bar{\tau}_{SBL}$ of the standard non-manipulated channel flow. The low-shear zones extend to large x^+ values in the case of D blowing showing the strong stabilization of the near wall activity in this case. In the case of sinusoidal blowing, in return, the low shear zones (dark zones in the Fig.) are concentrated near the slot. They are relatively more intense and extend until $x^+ \approx 100$ downstream compared with $x^+ \approx 300$ of the D case. Furthermore, SB induces locally the destabilization and roll-up of the positive vorticity layer induced by blowing.

The λ_2 technique (Jeong and Hussain, 1995) to educe the coherent vortical structures responsible of turbulent drag was applied to D and S blowing. This technique is based on the second negative eigenvalue of the $\mathbf{S^2} + \mathbf{W^2}$ where $S_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right)$ is the symmetric and $-_{ij} = \frac{1}{2}\left(u_{i,j} - u_{j,i}\right)$ is the antisymmetric components and $u_{i,j} = \frac{\partial u_i}{\partial x_j}$ is the derivative of the instantaneous velocity component u_i in the x_j direction ($i = 1,2,3$ correspond respectively to streamwise, wall normal and spanwise directions). Fig. 7 compares the contours of λ_2 in S and D blowing at the same time t/T. The decrease of the near wall turbulence activity in the D case is clearly seen in this Fig. This is more clearly seen in Fig. 8 that shows the λ_2 contours in the (x^+,z^+) plane.

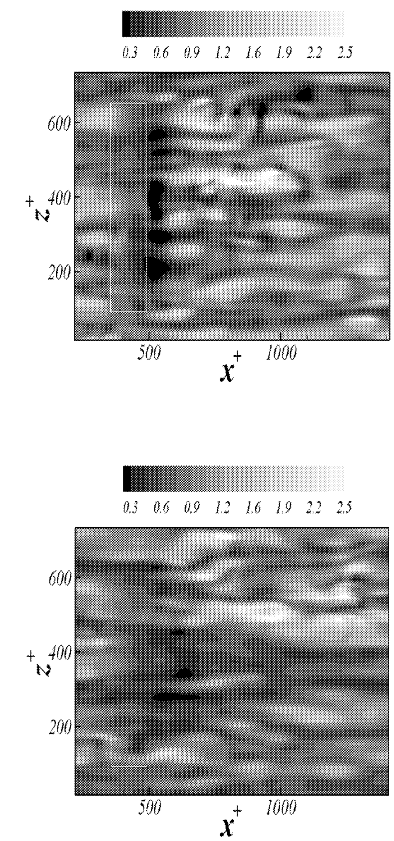


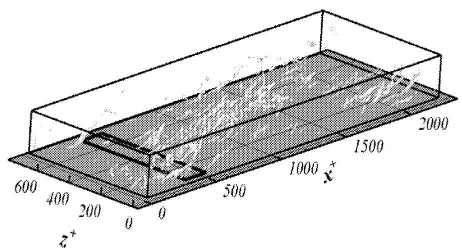
Figure 6 Wall shear stress in the case of sinusoidal (a) and dissymmetric (b) blowing. The dark zones correspond to low shear layers. Note how the letter ere extended in the streamwise direction in the case of D blowing(b), and the high shear packets in the case of S blowing (a). The slot is indicated by light rectangle in both figures.

DISCUSSION

Both the experiments and direct numerical simulations show that the relaminarized phase next to the slot relaxes slowly in the DB case. The turbulent transport transverse to the main flow direction is no more governed by the local shear under these circumstances. The streamwise gradient of the shear is no longer negligibly small in particular in the neighborhood of the induced low shear region. The change of this gradient is relatively rapid compared with the memory time of the turbulence and the fluid particles remember the shear upstream. According to Hinze (1975, p.391) the relaxation effect of this kind on Reynolds shear stress can be expressed as:

$$-\langle uv\rangle^+ = \nu_t^+ \left| \frac{\partial\langle u\rangle^+}{\partial y^+} - T_m^+\langle u\rangle^+ \frac{\partial^2\langle u\rangle^+}{\partial y^+\partial x^+} \right| \qquad (1)$$

a



b

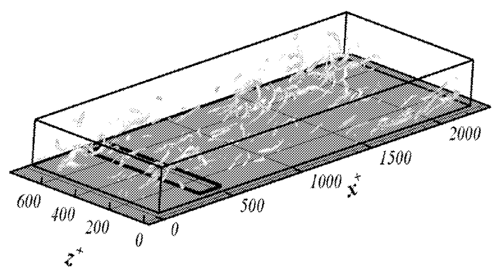
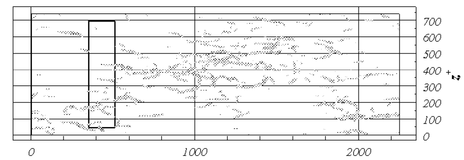


Figure 7 The contours of λ_2 in sinusoidal blowing (a) compared with dissymmetric blowing (b).

where ν_t^+ is the eddy viscosity and T_m^+ is the memory (relaxation) time. $T_m^+ \approx 100$ in canonical viscous region, The streamwise gradient of the shear $\frac{\partial^2\langle u\rangle^+}{\partial y^+\partial x^+}$ is positive near the frontier of the relaminarized zone downstream of the slot, and the turbulence transport is consequently reduced by the relaxation effect. The higher concentration of the induced vorticity in the low buffer layer results in sharper $\frac{\partial^2\langle u\rangle^+}{\partial y^+\partial x^+}$ in the case of unsteady high frequency blowing. This effect is further reinforced by DB, simply because the latter prevents the formation of the strong vortical structure that naturally enhances the mixing in the SB case.

a



b x^+

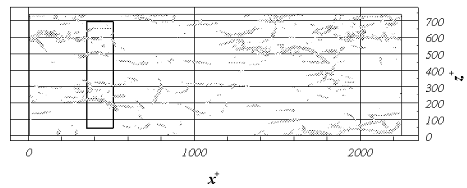


Figure 8 λ_2 contours in (x^+, z^+)plane. a- Sinusoidal, b- Dissymmetric blowing.

CONCLUSION

The results presented here show how the reaction of the near wall turbulence and of the drag are sensitive to the temporal waveform of the localized time periodical blowing. The injection velocity dissymmetric in time with a rapid acceleration followed by a slow deceleration phase prevents the roll up of the induced vorticity into an intense spanwise structure otherwise observed when the periodical blowing is sinusoidal in time. The D blowing allows also the spreading of the induced vorticity opposite to that of the basic flow further downstream of the intervention zone and results in an important drag reduction of nearly 60 % at the mean near the slot with relaminarization occurring during 70 % of the oscillation period. We are currently involving in the determination of the optimal temporal waveform of localized blowing by making use of direct numerical simulations. We also investigate suboptimal control behind the localized D blowing slot to see whether a reasonably large scale distribution of the MEMS can give rise to significant drag reduction or not.

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