LOCALIZED UNSTEADY BLOWING AND NEAR WALL TURBULENCE CONTROL

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ABSTRACT

The effect of time-periodical blowing through a spanwise slot on the near wall turbulence characteristics is investigated. The blowing velocity changes in a cyclic manner from 0 to 5 wall units. The frequency of the oscillations is equal to the median frequency of the wall turbulence. The flow field near the blowing slot is partly relaminarized during the acceleration phase of the injection velocity until 40 wall units downstream. The imposed unsteadiness is confined into the buffer layer and the time mean structural parameters under unsteady blowing are found close to those of an isotropic turbulence in this zone. The relaminarized phase is unstable and gives place to a coherent spanwise structure which, in return, increases the shear from 80 to 300 wall units downstream of the slot in a predictible way.

1. INTRODUCTION

It has recently been shown through direct numerical simulations that it is possible to control the near wall turbulence by either using suboptimal schemes (Bewley et al.,1993) or adaptive nonlinear methods (neural networks, Lee et al., 1997). The physical application of these methods requires however an inacceptably dense distribution of the sensors and actuators at the wall. The streamwise and spanwise spacings of these *MEMS* have to be as small as the viscous sublayer thickness in order to obtain an appreciable drag reduction of about 20%. Therefore and despite the progresses achieved now in micro -technology, the feasibility of these strategies may still be under question. Another method could use a robust-control-like strategy by first slightly forcing the near wall turbulence, determining subsequently its frequency response and introducing finaly local suboptimal control with eventualy *coarser and feasible distribution of MEMS* depending upon the reaction of the near wall flow. This study deals with the first part of these ideas, namely the reaction of the near wall turbulence to a time periodical forcing through a localized oscillating blowing. The achievement of this strategy poses the problem of optimal control of periodicaly perturbed (cyclostationnary) flows, which is a quite attractive theoretical challenge.

2. DEFINITIONS, EXPERIMENTAL SET-UP and DATA REDUCTION

2.1. Experimental set-up

An experimental model has been developed in the low-speed wind tunnel of our laboratory (Fig.1). The blowing and suction at the wall are done through spanwise slots of dimensions 0.6*100 mm which correspond to 10*1667 in wall units. There are one blowing and one suction slot by wavelength $\Lambda = 45$ mm. ($\Lambda^+ = 750$) and the pulsed surface recovers a total length of 3Λ i.e 2250 in wall units. Hereafter ($^+$) denotes values nondimensionalized with the inner variables, i.e the shear velocity $u_\tau = \sqrt{\tau/\rho}$ and the kinematic viscosity ν. *Only* results obtained through one *local unsteady blowing* slot are presented here.

A special pulsating device has been designed for the present purpose. Quite satisfactory sinusoidal waveforms of the suction/blowing wall normal velocities have been obtained for the amplitude of the imposed velocities up to $A_{v\text{-}y^+=0} = \widehat{A} = 1.5$ m/s ($\widehat{A}^+ = 8$) and the imposed frequency 10Hz<f<50Hz ($2.5*10^{-3}<f^+<12.5*10^{-3}$). The time mean, amplitude and the phase shifts between blowing/suction slots may be changed independently.

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). The length of the sensing element is 200 µm which corresponds to a spanwise extend of $\Delta_z^+ \approx 3$ at X=1 m. from the transition point with $\overline{U}_\infty = 4$ m/s . The total duration of each record is $T_{tot} \approx 5000\, T_\infty$ where $T_\infty = \delta/U_\infty$ is the outer time scale. This is enough to ensure the convergence of the statistics up to 4th order moments including those of the time derivative of the fluctuating signals.

One should be carefull in the interpretation of data in the presence of an organized motion as is the case with unsteady blowing in this study. 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 $\overline{q}$ an oscillating $\widetilde{q}$

and a fluctuating q' part, i.e: $q(\vec{x}, t; T) = \bar{q}(\vec{x}) + \tilde{q}(\vec{x}, t/T)$, $+ q'(\vec{x}, t)$ where T stands for the period of the oscillating blowing. The ensemble or the phase average is performed in order to determine the amplitude $A_{\tilde{q}}$ and phase $\Phi_{\tilde{q}}$ of the oscillating part $\tilde{q}$ from which the instantaneous fluctuating part q' is adequately deduced. The beginning of each cycle is provided by a pulse from a photoelectric cell triggered by the pulsator, and the trigger signal was also recorded. The modulation characteristics have been determined through a least square Fourier analysis.

2.2.Experimental conditions; Blowing severity

In flows with uniformly distributed continuous blowing/suction (transpired layers through porous surface), the parameter which characterizes the intervention at the wall is given by $B_f = \frac{\bar{v}_0 \bar{U}_\infty}{\bar{u}_\tau^2} = \bar{v}_0^+ \bar{U}_\infty^+$ where $\bar{v}_0$ stands for the injection/suction velocity at the wall. The local suction/blowing, however, involves phenomena related to the relaxation of near wall turbulence downstream of the intervention zone. The ratio of the injection or suction flow to the *incoming* flow rate, i.e $\Theta = v_0 L_x / \int_0^\infty \bar{U} dy$ is therefore introduced and proved to be adequate to measure the blowing/suction severity (Sano and Hirayama ,1985; Sokolov and Antonia (1993).

We proceeded with particularly small slot widths compared with previous studies quoted above. As a consequence, the severity parameter is low. The injection velocity in steady blowing experiments investigated here is $\bar{v}_0$= 1m/s and the severity parameter is only Θ = 0.006 . 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 Θ= 0.012 and the maximum shape parameter is H=1.6 which is below the limit of flows prone to separate.

3. RESULTS

One of the main aims of this study is to determine whether a periodic time-varying blowing of the form $\tilde{v}_0^+ = \hat{A}^+ (1\text{-}\cos 2\pi f^+ t^+)$ affects the near wall turbulence characteristics when compared with a steady injection by slot with the same time-mean blowing velocity $\bar{v}_0^+ = \bar{\tilde{v}}_0^+ = \hat{A}^+$ resulting in the same time mean severity parameter $\Theta = <\Theta>$. In other words, the question is whether the near wall flow interacts at the maen with the imposed unsteadiness or not. Therefore, we will systematically compare the mean flow characteristics obtained with unsteady and steady blowing hereafter. Before discussing the results, the *notation* needs to be clarified. We have 3 flow configurations here, namely the standard boundary layer (SBL), the manipulated boundary layer (MBL) under steady and unsteady blowing. Here, an asterisk (*) refers to quantities measured in the manipulated boundary layer, while the subscript S indicates steady blowing. In a similar manner, the subindex U corresponds to unsteady blowing and the subindex SBL refers to the standard unmanipulated boundary layer.

The ensemble of the results presented here are obtained with an imposed frequency $f^+ = fv/u_{\tau SBL}^2 = 0.017$ with $\hat{A}^+ = 5$. The Reynolds number of SBL is $Re_\theta = 10^3$. Only part of the results obtained at x^+<40 downstream of the slit in which the flow is partly relaminarized could be discussed here.

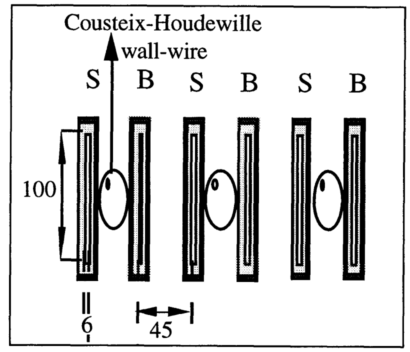


Figure 1. Are shown the slots and their dimensions in mm. S and B refers to suction and blowing respectively and they may be phase-shifted. *Only one blowing slot* is used here.

3.1. Time mean flow

Fig. 2a shows the time mean streamwise velocity profiles in the standard boundary layer and in the presence of both steady and unsteady blowing at x^+=40 downstream of the slot. The velocity $\bar{u}$ and the wall normal coordinate y are scaled with the local inner variables i.e by $\bar{u}_{\tau SBL}$ in the SBL and $\bar{u}^*_{\tau S}$ or $\bar{u}^*_{\tau U}$ in the manipulated boundary layer. The first streaking feature of the results summarized in Fig.2a is the insensitivity of the time mean streamwise velocity profiles to the imposed unsteadiness. It is indeed seen that both $\bar{u}_S^{*+}$ and $\bar{u}_U^{*+} = \overline{<u>}^+$ corresponding respectively to steady and unsteady blowing collapse fairly well in the entire boundary layer. The wall shear stress is also unaffected at the mean, by oscillating blowing at this particular station and $\bar{\tau}_S^* = \bar{\tau}_U^* = 0.67\ \bar{\tau}_{SBL}$.

One distinguishes easily in Fig. 2a between the viscous sublayer, the buffer layer and the log-layer in the MBL in the same way as in the canonical boundary layer. The viscous sublayer is considerably thickened in the presence of blowing and one has $\bar{u}_S^{*+} \approx \bar{u}_U^{*+} = y^+$ at $y^+ <12$. Note also that the velocity profiles collapse well with $\bar{u}^{*+} = 2.5 \ln y^+ + 10.5$ for $y^+ > 40$ pointing at the existence of a constant shear layer with time mean equilibrium. The buffer layer, on the other hand, is somewhat thinned and extends from only $y^+ = 12$ to $y^+ = 40$.

The upward shift observed in the log region of the manipulated boundary layer is in agreement with the direct numerical simulations conducted by Choi and all. (1997) who investigated the effects of steady blowing and suction from a spanwise slot. This is, by the way, a common feature of drag reducing effects and is a direct consequence of the thickening of the viscous sublayer and vice versa. This may be shown by different ways, for example by the Rotta's model (1950). Rotta used the Prandtl mixing-length hypothesis and modelled the shear stress as $\partial\bar{u}^+/\partial y^+ - \overline{u'v'}^+ = \left[1 + l_m^{+2}\, \partial\bar{u}^+/\partial y^+\right] \partial\bar{u}^+/\partial y^+ = 1$, where contrarily to the classical theory, the mixing length is $l_m^+ = \chi\left(y^+ - \delta_v^+\right)$, with δ_v^+ standing for the thickness of the viscous sublayer in wall units and χ the von Karman's universal constant. The streamwise velocity distribution resulting from this closure reads for $\bar{u}^+ = A \ln y^+ + B$ at large values of y^+ with $A = 1/\chi$ and $B = (\ln 4\chi - 1)/\chi + \delta_v^+$. Taking $\chi = 0.4$ and $\bar{\delta}_{v\,S}^+ \approx \bar{\delta}_{v\,U}^+ = 12$ in the manipulated boundary layer, leads to B=10.6 which is in close agreement with the results summarized in Fig. 2a.

Both the time mean turbulence intensity $u'^+ = \sqrt{\overline{u'u'}} / \bar{u}_{\tau\,SBL}$ and the wall normal distance y are scaled with the local shear velocity of the *unmanipulated* boundary layer in Fig.2b. The main effect of blowing is clearly the shift away of the near wall spanwise vorticity since near the wall $u'_\infty - \omega'_{z,0}\, y$ with $\omega'_{z,0}$ beeing the fluctuating spanwise vorticity at y=0. The removal of $\omega'_{z,0}$ results in a virtual origin of $\sqrt{\overline{u'u'}}$ of about $\Delta y^+ = 2$ under both unsteady and steady blowing. It is further seen in Fig. 2b that, in the presence of unsteady blowing u'^{*+}_U reaches its maximum at $y^+=10$ somewhat earlier than u'^{*+}_S. It keeps its maximum further away in the whole buffer layer $10<y^+<40$. This unexpected reaction shows that the imposed unsteadiness increases mixing in the inner layer although somewhat slightly.

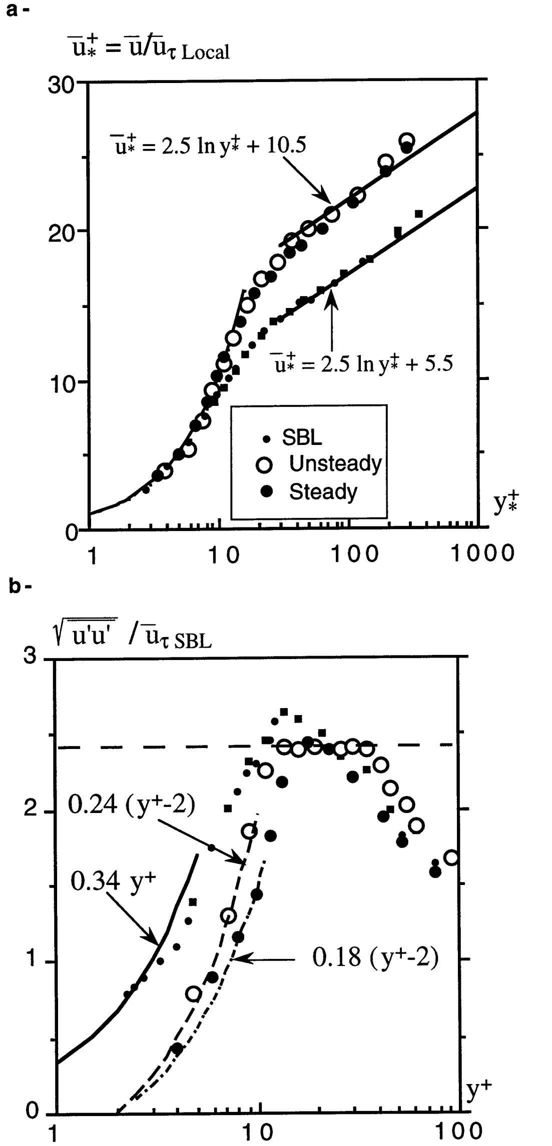
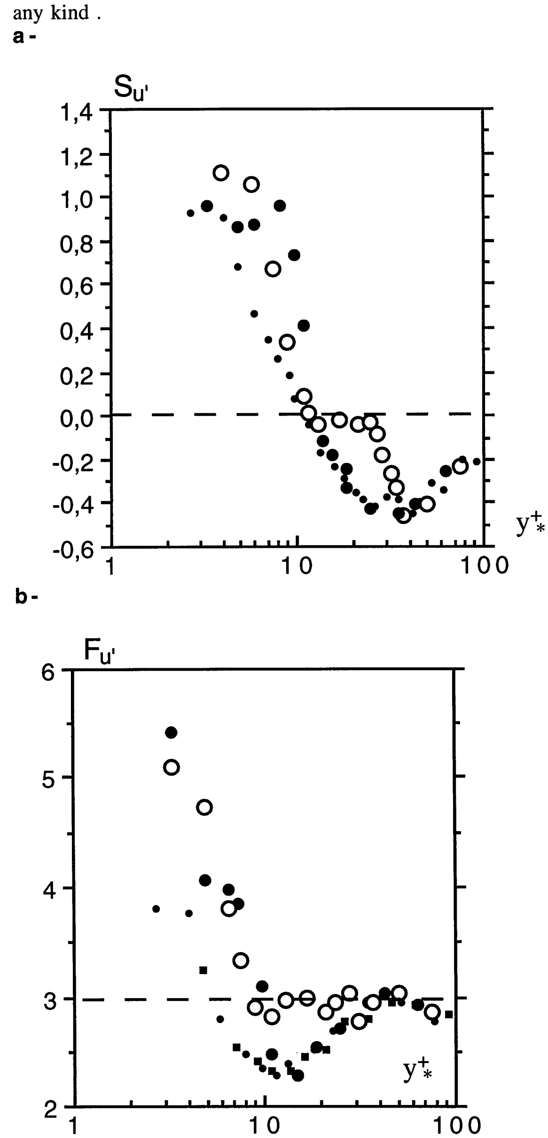


Figure 2.. a- Time mean velocity scaled with local shear velocity; b- Longitudinal turbulent intensity scaled with the shear velocity of the standard boundary layer ($x^+=40$).

The repercussion of the local oscillating blowing on the fine structure of turbulence is analyzed through the distributions of the skewness and flatness factors of u' and its time derivative shown in Fig. 3. The effect of the imposed unsteadiness in the whole buffer layer is streaking: The skewness and the flatness of u' at $10<y^+<30$ are respectively $S_{u'} \approx 0$ and $F_{u'} \approx 3$ when the blowing is unsteady. Furthermore, the skewness of the time derivative du'/dt is (Fig. 3c) is close to 0.3 in this zone a value which is significantly different compared with 1 of the unmanipulated buffer layer. These characteristics are nothing but those of an *isotropic* turbulence. The steady blowing, on the other hand, does not appreciably affect these structural quantities compared with the SBL. The oscillating blowing acts presumably as an "*isotropening* "-whitening- filter at the *time-mean* sense near the wall under the present working conditions. The term *at the mean* has to be emphasized since the flow quantities are strongly modulated in the buffer layer. The author is not aware of such a strong interaction with the small scale turbulence, caused by an excitation of any kind .



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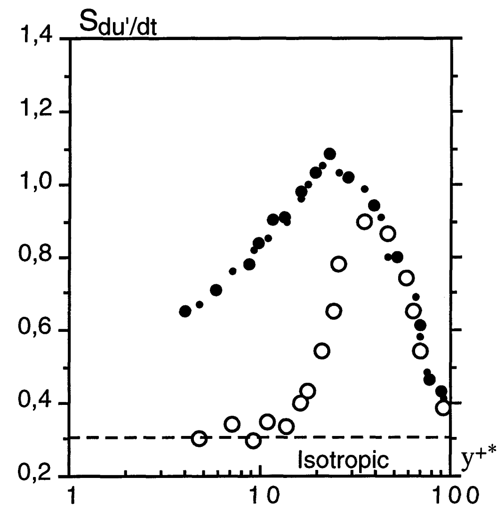

Figure 3. Fine structure of turbulence under unsteady and steady blowing; a- Skewness, b- Flatness of fluctuating longitudinal velocity, c- Skewness of the time derivative of the streamwise fluctuating velocity. Symbols identical to those of Fig. 2

3.2. Phase averages

Fig. 4a shows the cyclic modulation of the wall shear stress at $x^+=20$ and 40 downstream of the slit. The reaction of $<\tau>$ is striking during the acceleration phase of the injection velocity. The wall shear stress decreases rapidly during this phase until it reaches the laminar limit defined as the value that a laminar Blasius boundary layer would have at the same Reynolds number. The corresponding phase averages of the wall shear stress intensity $<\tau'\tau'>/\overline{\tau'\tau'}_{SBL}$ are shown in Fig. 4b. The near wall turbulence activity is totally suppressed at $x^+=20$ during half of the oscillation cycle coinciding once more with the acceleration phase of $<v_0>$. At $x^+=40$ there is a slight increase both in $<\tau>$ and $<\tau'\tau'>$ at t/T= 0.6 and this will be discussed in the next section.

The strong modification of the wall turbulence structure is better captured in Fig.5 which shows the phase average of the skewness $<S_{du'/dt}>$ of the time derivative of fluctuating streamwise velocity du'/dt and of the ejection frequency $<f_e^{+*}> = <f_e>\nu/\overline{u}_\tau^{*2}$ identified by VITA through the phase averaged thresholds at $y^+= 12$. Recall that $<S_{du'/dt}>$ is related to the production of mean square streamwise vorticity by stretching and the non linearity in the inner layer. Fig. 5 shows that both the vorticity generation and production mechanisms are altered at high blowing frequency during half of the oscillation cycle. At the acceleration phase, the bursting activity together with the vortex stretching are largely suppressed. These effects are confined into the buffer layer beyond which the modulation of flow quantities decreases sharply.

Further comments are needed concerning the peculiar behaviour of $<S_{du'/dt}>$ shown in Fig. 5. It is clearly seen that $<S_{du'/dt}>$ have large *negative* values at 0.4<t/T<0.8 during the acceleration phase, contrarily to the SBL wherein $S_{du'/dt} >0$ and is large. In isotropic homogeneous turbulence negative $S_{du'/dt}$ would mean inverse inertial transfer of energy across the wave number domain and rapid destruction of the mean square vorticity by compression i.e the suppression of nonlinear mechanisms ! Although, in a configuration such as in near wall turbulence which is highly anisotropic and nonhomogeneous such interpretations are of qualitative nature, this highly strong effect of the unsteady local blowing on the nonlinear mechanisms governing the near wall turbulence is worthwile.

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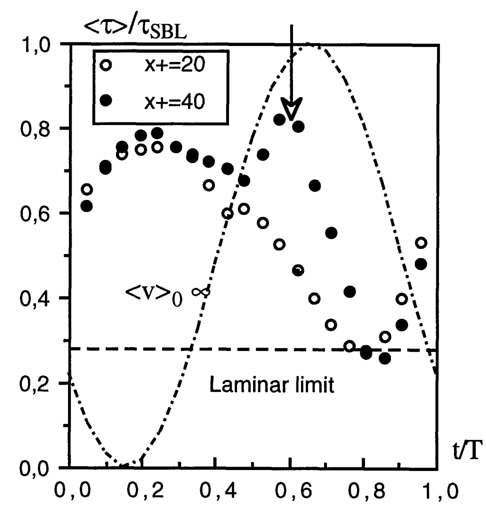

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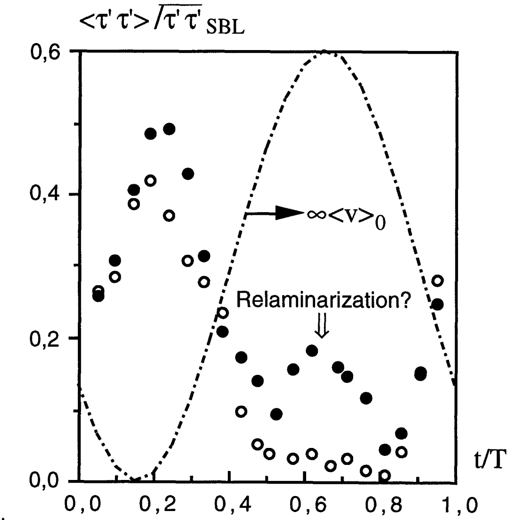

Figure 4. Phase averages of the wall shear stress (a) and wall shear stress intensity (b) at $x^+=20$ and 40 downstream of the injection slit. The imposed frequency is still $f^+=0.017$.

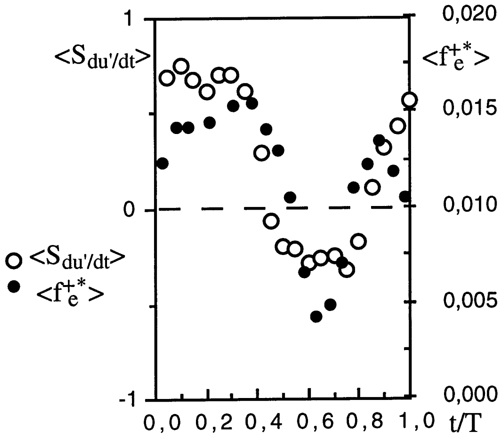

Figure 5. Phase averages of the skewness of time derivative of u' and the ejection frequency determined by VITA using modulated thresholds as in Tardu and Binder (1997) at $y^+=12$.

3.3 Birth of a coherent spanwise structure

The space time evolution of the near wall flow at further downstream locations is striking. First the velocity profiles become strongly inflexional at $x^+=40$ and approximately in the middle of the *deceleration* phase. Fig. 6a shows the phase averaged velocity profiles at t/T=0.4 (for reference) and t/T=0.8 corresponding respectively to the middle of the acceleration and deceleration phases of the injection velocity. The presence of an inflexional point at t/T=0.8 where $<\tau>$ decreases to the laminar limit (Fig.4), is clear. It may, therefore, be argued that the *relaminarized* flow is possibly unstable to inviscid disturbances according to the Fjortoft's theorem. This behaviour is somewhat consistent with the general idea that time or space deceleration destabilizes the flow. It is emphasized here that the close inspectation of the phase averaged streamwise velocity profiles showed that the local gradient is never zero and that the vorticity does not change sign. Therefore, the observed behaviour is not due to a local unsteady separation according

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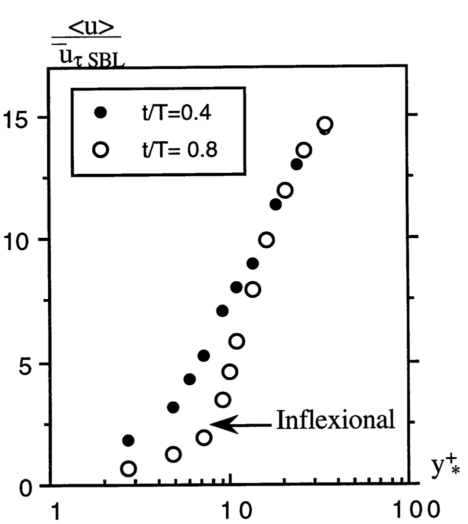

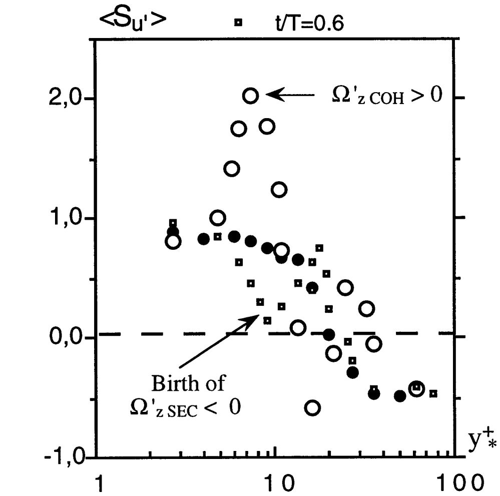

Figure 6. Distribution of (a) the streamwise velocity, and (b) the skewness of u' at t/T=0.4-0.8 and $x^+=40$. The birth of $\Omega'_{z\,SEC} < 0$ is seen in (b) at t/T=0.6.

to the Moore-Sears criteria. The unstabilized flow enters subsequently into *retransition* further downstream following the scheme reported by Narasimha and Sreenivasan (1973). This gives place to the accumulation and enhancement of a patch of spanwise vorticity *of the opposite sign* to the mean vorticity during the deceleration phase at t/T=0.8. The existence of this coherent patch may be clearly seen by the local maximum and minimum appearing in the $\sqrt{<u'u'>} / \bar{u}_{\tau\,SBL}$ profile (could not be shown here). The fact that it is positive may be understood through the sudden changes in the skewness of u' shown in Fig.6b and the mechanism suggested schematicaly in Fig. 8. This patch rolls up into a coherent structure $\Omega'_{z\,COH} > 0$ approximately at $y^+= 12$. Fig. 8 gives a possible explanation of the effect of this coherent structure on the velocity profiles where it is suggested that $\Omega'_{z\,COH} > 0$ may accentuate the inflexion.The birth of this structure (its origin is approximately at $x^+=20$), in return, gives place downstream to a secondary spanwise vortical structure near the wall with opposite sign, i.e $\Omega'_{z\,SEC} < 0$, because of the non slip condition.The genesis of $\Omega'_{z\,SEC} < 0$ and its subsequent development are perfectly well localized both in time and space (the vortex-ring-like structure -similar to the streamwise Falco typical eddy- in Fig 8 is only suggestive for the moment). The whole structure is convected downstream with an advection velocity of $7\bar{u}_{\tau\,SBL}$, while $\Omega'_{z\,SEC} < 0$ is reinforced and $\Omega'_{z\,COH} > 0$ diffuses somewhat more rapidly. Consequently the wall shear stress increases almost in a Dirac function fashion at times and locations which are perfectly predictible as shown in Fig. 7. The whole phenomena relaxes further downstream at $x^+=300$ (not shown here). This mechanism occurs in the high frequency regime, for $f^+>0.007$ approximately. Therefore, it can nicely be used to *increase* the drag and prevent unsteady separation and/or to *decrease* it through distributed *blowing* locations and by *frequency modulation*. only with negligeable cost. On the other hand, the combination of phase shifted blowing/suction at $x^+>40$ may be efficient for the space-time control of $\Omega'_{z\,COH} > 0$.

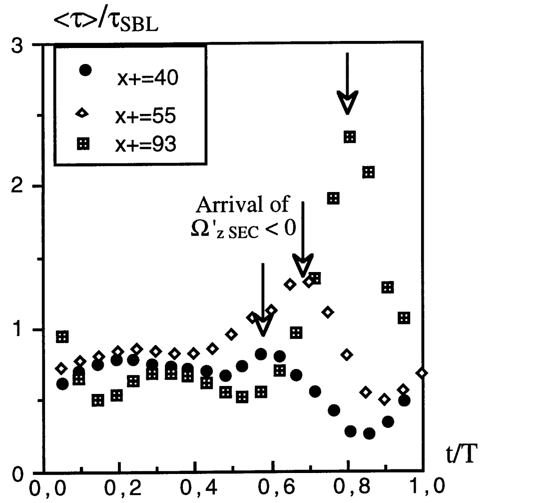

Figure 7. Phase average of the wall shear stress at further downstream positions

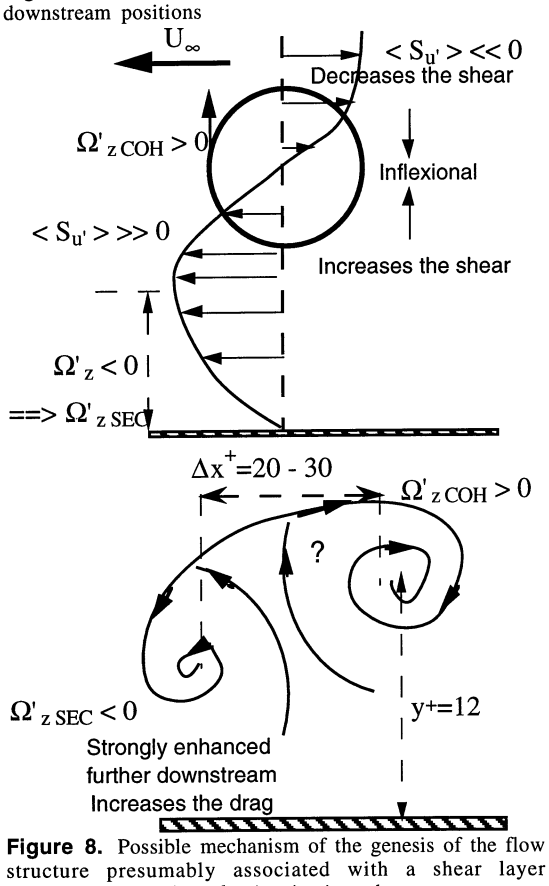

Figure 8. Possible mechanism of the genesis of the flow structure presumably associated with a shear layer instability during the *relaminarization* phase.

4. DISCUSSION and CONCLUSION

The ensemble of the ingredients characteristic of relaminarization are present near the slot at $x^+< 40$ and during half of the cycle namely:

*The wall shear stress decreases considerably until reaching the value that a laminar boundary layer would have at the same Reynolds number.

*Dissipation dominates the near wall flow which is stabilized.

*The velocity fluctuations in the inner layer are not zero but their contribution to the dynamics of the flow becomes inconsequential.

*The frequency of active Reynolds stress producing events decrease considerably and a thin region near the wall extending to approximately 2-3 wall units grows from the wall being free of fluctuating streamwise vorticity. The thickness of this zone reaches almost 5 wall units during half of the oscillation cycle.

* The stretching of quasi-streamwise vorticity decreases strongly as indicated by even negative value of the skewness of the streamwise velocity fluctuations. This part of the oscillation cycle coincides also with large decreases of the Taylor time scale indicating the set-up of small scale turbulence.

In the case of blowing there is no substraction or addition of vorticity. The spanwise mean and fluctuating vorticity, together with *turbulent-drag* inducing quasi-streamwise vortical structures (QS) are displaced and pushed away from the wall. This is subsequently corrected by the formation of a thin vortex sheet in front of the wall (and of its image) with vorticity of opposite sign to the mean vorticity. This sheet subsequently dilutes through diffusion. It turns out that, in the decelaration phase and when the imposed unsteadiness is sufficiently rapid, there is a net accumulation of this sheet leading to $\Omega'_{z\ COH} > 0$ after roll-up which in return induces $\Omega'_{z\ SEC} <0$. This phase coincides with the uncoupling with the near wall flow of removed QS's, resulting in a temporal relaminarization. These are real unsteady effects occuring only when the blowing frequency is larger than a critical value. The ensemble of the results presented here shows how a time varying intervention at the wall may involve complex phenomena. It is hopped that they may provide new perspectives in the near wall control, through a combination of phase-shifted and eventualy frequency modulated local blowing/suction sites.

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