EFFECT OF SUCTION APPLIED THROUGH A PAIR OF POROUS WALL STRIPS, ON A TURBULENT BOUNDARY LAYER

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ABSTRACT

Hot-wire measurements have been made in a turbulent boundary layer subjected to concentrated suction, applied through two porous wall strips. The results indicate that the use of a second strip increases the total skin friction reduction over one suction strip. The use of two strips extends the relaminarisation zone but also reduces the overshoot in the longitudinal and normal rms velocities. While the minimum rms occurs at $x/\delta_0 = 3.0$ (one strip) and $x/\delta_0 = 12$ (two strips), the reduction observed for the latter case is larger. The rather large streamwise distance over which the reduction of C_f occurs may reflect the effect suction has on the large-scale structures. The effect is enhanced with two strips because the second strip acts on a boundary layer whose Reynolds number has been reduced by the first strip and whose near-wall active motion has been seriously weakened.

INTRODUCTION

Considerable effort has been devoted on the control of natural laminar-turbulent transition using various techniques (e.g. Biringen (1984), Reed et al. (1996), Cathalifaud and Luchini (2000)). Out of all the tested techniques, suction has been found useful for controlling the flow, in particular for delaying transition and separation (Gad-el-Hak et al. (1998), Gad-el-Hak (1989)). The application of suction on a turbulent boundary layer through a single narrow porous wall strip / slit has been widely studied for quite a number of reasons (e.g. Sano and Hirayama (1985), Antonia et al. (1988), Antonia et al. (1995), Oyewola et al. (2001), Pailhas et al. (1991), Merigaud et al. (1996)). For example, the manner in which the near-wall coherent structures respond to the suction could provide some insight into the interaction between the wall region and outer part of the boundary layer. Under certain conditions, relaminarisation can be achieved immediately downstream of the strip (Antonia et al. (1995), Antonia and Sokolov (1993), Oyewola et al. (2001)). The results from previous studies (Oyewola et al. (2001, 2002)) show that both the suction rate and the momentum thickness Reynolds number can influence this relaminarisation. The retransition which occurs further downstream of the suction strip can be controlled. It was suggested by Oyewola et al. (2001, 2002) that one way of controlling this retransition would be to use a succession of suction strips. The present work exploits this latter suggestion and extends the work of Oyewola et al. (2001, 2002). The main objective of the present study is to assess the response of the layer to a concentrated suction applied through two separate successive porous strips. The second strip is placed at a streamwise location where local recovery from the first (upstream) strip begins. In this study, measurements of the skin friction over the two strips with and without suction are considered. Also, the effects of the double suction on the measured velocity fluctuations in the streamwise, normal and spanwise directions are considered for various streamwise x locations. The overall results are compared with those obtained when suction is applied through the first suction strip only.

EXPERIMENTAL DETAILS

Measurements were made in a newly constructed boundary layer wind tunnel, driven by a single-inlet 15 kW centrifugal fan, which is able to deliver up to a free stream velocity of 40 m/s. Air enters the working section (Figure 1) through a two-stage two-dimensional diffuser into the $1.6 * 0.9$ m^2 settling chamber. The chamber consists of six evenly spaced wire mesh screens and a 5 mm aluminium honeycomb. The settled air then flows through a 9.5:1 2-dimensional contraction. A turbulent boundary layer developed on the floor of the rectangular working section (see schematic arrangement in Figure 1) after it was tripped at the exit from the contraction using a 100 mm roughness strip. Tests showed that the boundary layer was fully developed at the suction strip location. The two-dimensionality of the flow was checked by measuring mean velocity profiles at a number of spanwise locations for some streamwise locations.

There were no systematic spanwise variations (maximum deviation was within ±4% of the centreline velocity).

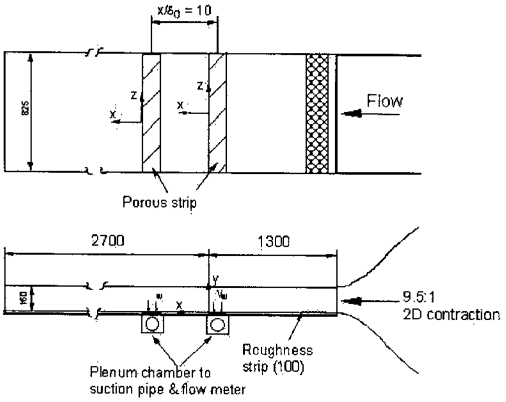

Fig. 1. Schematic arrangement of the test section

Two 3.25 mm thick porous strips of streamwise length 40 mm and made of sintered bronze with pore sizes in the range 40 – 80 μm or (0.4 – 0.9)$\nu/U_{\tau 0}$ (where, $U_{\tau 0}$ is the friction velocity with no suction and ν the kinematic viscosity) was mounted flush with the test section floor. Allowing for the width of the mounting recess steps, the effective width (=b) of the strip was 35 mm. The suction velocity (V_w) was assumed to be uniform over the porous surface; this assumption seems reasonable if the variation in the permeability coefficient of the porous material is ±3%.

The second porous strip is placed at a streamwise location of $x/\delta_0 \approx 10$; δ_0 is the boundary layer thickness at the leading edge of the first strip without suction being and the value is about 30 mm. Measurements with only the first porous strip activated showed that the perturbed boundary layer started to recover from this position (Oyewola et al. (2001, 2002)). The free-stream velocity U_1 is 3.25 m / s and the corresponding initial momentum thickness Reynolds number $R_{\theta 0}$ ($\equiv U_1\theta_0 / \nu$, where, θ_0 is the momentum thickness at the leading edge of the first suction strip when no suction is applied) is 750. The suction rate σ ($\equiv V_w b / \theta_0 U_1$, where, b is the width of the porous strip respectively) was 3.3 over the first strip (σ_1) and 2.0 over the second strip (σ_2). In order to assess the effectiveness of the strips, measurements were also made for $\sigma = 5.5$ applied through the first suction strip only. The combined suction flow rate (volumetric) Q_c ($= Q_1 + Q_2$, where, Q_1 and Q_2 are the flow rates for the first and second strips respectively) over two strips is less than that for one strip with $\sigma = 5.5$. The effect of suction is quantified by measuring the local wall shear stress, the mean velocity, and all the three-velocity fluctuations downstream of each suction strip. The local wall shear stress was measured with a Preston tube with an outer diameter of 0.72 mm (carefully calibrated in a fully developed turbulent channel flow using a similar method to that described in Shah and Antonia, 1989), and a static tube located approximately 35 mm above it at the same x position. Pressure differences were measured by a MKS Baratron pressure transducer whose output was averaged after digitising (400Hz) for approximately 120 s. The uncertainty in the measurement of skin friction was about ±5% using a propagation of error analysis. This was estimated by measuring the skin friction 10 times with records of about 60 s were recorded each time, at several streamwise x locations downstream of the strips. At each location, the uncertainty was ±5% of the mean value. Measurements of the mean velocity and the velocity fluctuations was carried out with single- and crossed-hot wire probes operated by an in house constant temperature anemometers at an overheat ratio of 1.5. The etched portion of each wire (Wollaston, Pt-10% Rh) had a diameter of 2.5 μm, and a length to diameter ratio of about 200. The Reynolds number based on the sensor length, $l^+ = lU_{\tau 0} / \nu$ (l is the length of the wire), was within 4 – 6. The analog output signal of the hot wire was low pass filtered at 800 – 1200 Hz, offset and amplified to within ± 5 V, then sampled and digitised at 1600 – 2400 Hz. A 40 s data record was used at each measurement station to ensure the convergence (to within ± 0.5%) of mean velocity and velocity fluctuations.

RESULTS AND DISCUSSION

The skin friction coefficient is plotted, with reference to no-suction case (C_{f0}), in Figure 2 for the double suction ($\sigma_1 = 3.3$ and $\sigma_2 = 2.0$). The C_f variation, when suction is applied at the first porous strip only ($\sigma = 5.5$), is also shown. The figure clearly shows that the second suction help keeping the C_f below that of the no-suction case over a longer downstream distance. Also, as expected, applying a second suction behind the first one generates a rise in the C_f. However, the rise (at x/δ_0

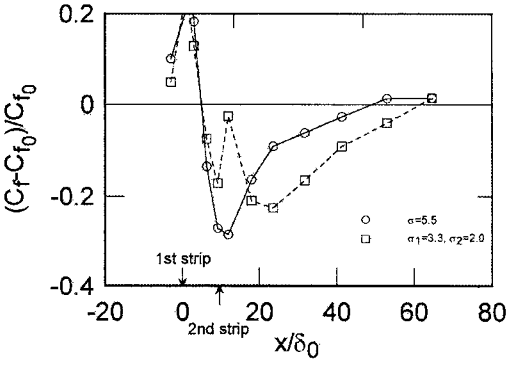

Fig. 2. Streamwise variation of skin friction coefficient. □: 2 strips; O: 1 strip.

= 12) lies below the value of C_{f0}. This is quite an interesting result with practical application. Indeed, it suggests that a series of successive suction with judiciously selected suction rates could help keep C_f below C_{f0} for a long distance at minimum cost.

For the present case, the use of the second suction increases the total skin friction reduction over the one obtained with the single suction (the areas comprised between the curves and the line corresponding to $\sigma = 0$ are 4.473, for one strip and 6.132, for two strips). The reason why the second suction increases the streamwise distance corresponding to a reduction in C_f is related to the reduction in the Reynolds number downstream of the first suction strip (Figure 3). This explains why the second rise in C_f is much lower than the first one. The suction from the second strip is effective since it acts on a boundary layer with a lower Reynolds number and with a near-wall region that has been strongly interfered with. Djenidi et al. (2002) showed, through flow visualisations, that the low speed streaks are significantly altered by the suction; for example, the streaks are less agitated. This is not surprising since the streaks are closely associated with the ejections and sweeps which are responsible for most of the shear stress in the inner layer (Bradshaw and Langer (1995). The reduction suggests that the drag-producing events are weakened by suction. The second application of suction would act on a dynamically "weakened" boundary layer, and therefore provide a more effective means of control than if only one strip were available.

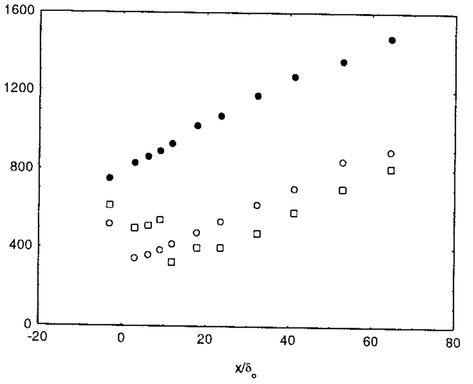

Fig. 3. Streamwise variation of momentum thickness Reynold number (R_θ). ●: $\sigma = 0$; □: 2 strips; O: 1 strip.

Distributions of the mean velocity, U^+, are shown in Figures 4a and 4b for one and two strips respectively, in terms of y^+ for different streamwise stations downstream of the porous strips (hereafter the superscript + will denote normalization by wall variables, i.e. the friction velocity U_τ and ν). Also shown in the figures are the Blasius profile and the DNS distributions of Spalart at $R_\theta = 1410$. Results for $\sigma = 0$ are shown in both figures in order to provide a reference against which the effect of suction can be assessed. Despite the small value of $R_{\theta 0}$ (750), the distributions for $\sigma = 0$ are consistent with an approximately self preserving turbulent boundary layer, and compare well with the DNS distributions of Spalart (1988) as shown in the figures taking into account the difference in R_θ.

The data collapse onto the no suction profile in the region below $y^+ \leq 10$, highlighting the rapid response of the mean velocity to a change in boundary condition. The scatter of some of the data set in this region, especially for $y^+ < 5$ is partially due to heat conduction into the wall from the hot-wire.

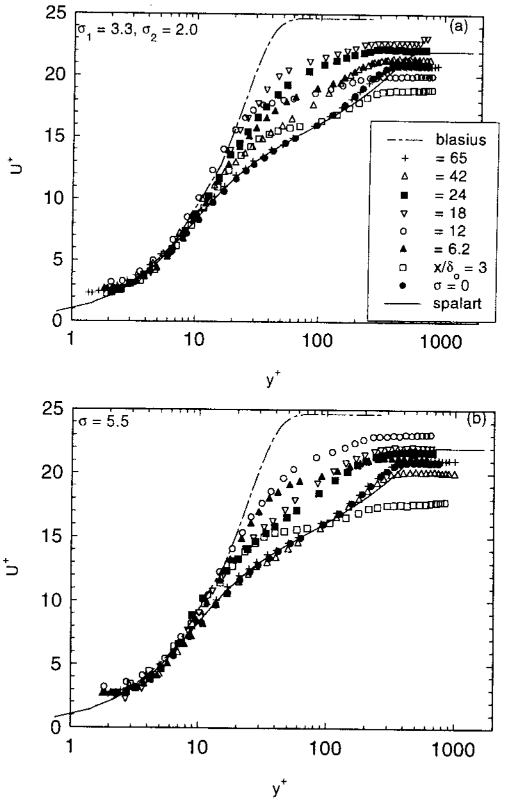

Fig. 4. Mean velocity distributions. (a) two strips; (b) one strip.

In both cases (one and two strips) there exists a noticeable change in the velocity distribution relative to the zero-suction profile for all positions up to $x / \delta_0 = 42$. This is consistent with the C_f distribution (Fig. 2). The U^+ distribution with the two suction strips active, shows the effect of the second strip on the already perturbed boundary layer. Note that recovery towards the undisturbed profile is postponed with the use of the second suction: with one suction strip the recovery starts at about $x / \delta_0 \approx 12$; with the double suction, the recovery starts at x / δ_0 comprised between 18 and 24. Note though that in both cases the profile have returned to the undisturbed profile at $x / \delta_0 = 65$. This delaying effect of the second suction strip on the recovery of the boundary layer was already noticeable in Figure 3, where the minimum value of R_θ occurs at $x / \delta_0 \approx 20$ for the double suction and $x / \delta_0 \approx 8$ for the single suction. It is interesting to note that the minimum value of R_θ is about the same for both cases.

The streamwise variations of the velocity fluctuations (RMS) in the longitudinal (u'^+), and transverse (v'^+) directions, and the Reynolds shear stress ($-u^+v^+$) for both cases of suction are shown in figures 5 and 6 respectively. The distributions for $\sigma = 0$ and the DNS data of Spalart (1988) for $R_\theta = 1410$ are also shown for comparison.

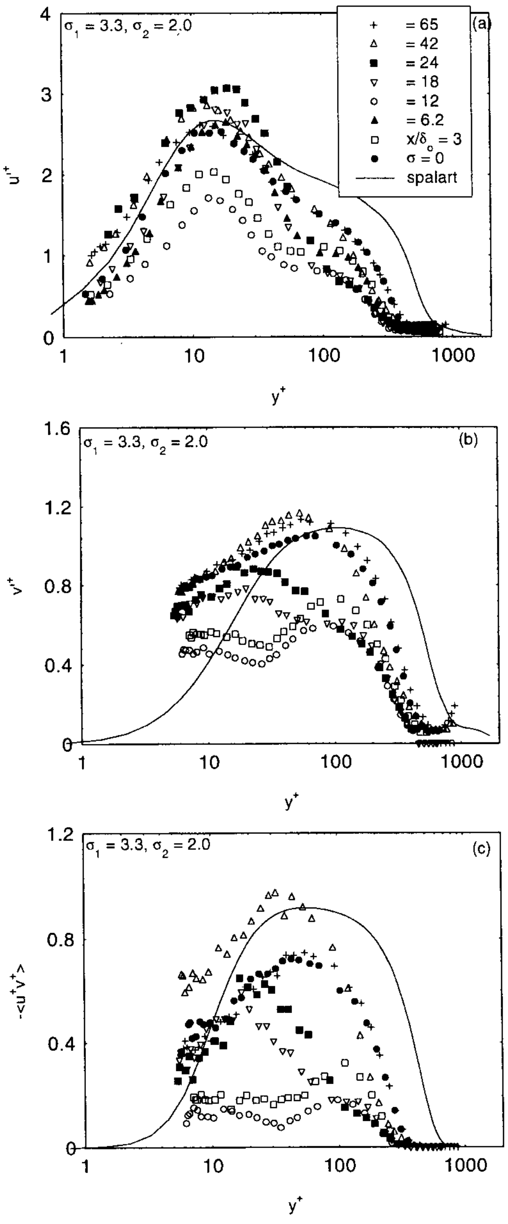

Fig. 5. Streamwise variation of (a) u'^+; (b) v'^+; (c) $-u^+v^+$ for two suction strips. All symbols are as in (a).

In general the RMS distributions as well as the Reynolds shear stress with the two suction strips active are significantly lower than those for one active strip in the region $12 \le x/\delta_0 < 42$, highlighting the cumulative effect of the double suction. The second suction acts, in a relatively similar manner as the first suction, on a turbulent field weakened by the first suction. An important consequence of this double suction is on the overshoot of the u^+ distribution. This latter is significantly reduced with two suction strips, suggesting that the layer has been dynamically weakened.

A practical application of this, would be to have a series of suction strips which act on successively weakened turbulent layers so that relaminarisation is achieved gradually.

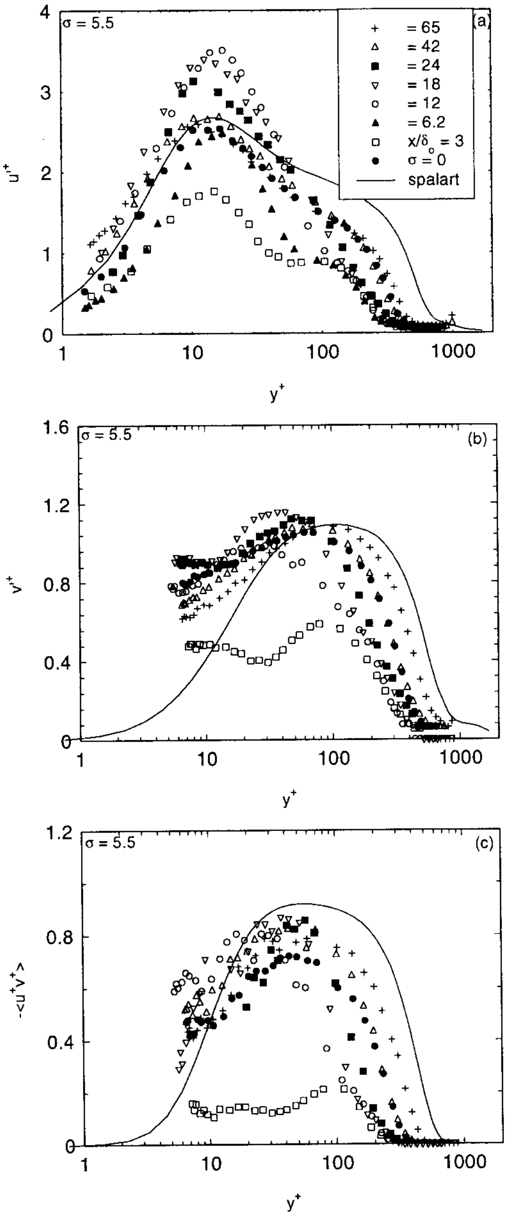

Fig. 6. Streamwise variation of (a) u'^+; (b) v'^+; (c) $-u^+v^+$ for one suction strip. All symbols are as in (a).

Figure 7 shows the streamwise variations of the maximum values of u'^+, v'^+, normalised by the unperturbed counterpart values. Firstly, an oscillation on both quantities is observed. Secondly, after introducing the second strip, the amplitude of the oscillation reduces. The overshoot observed in u'^+ and v'^+ were reduced and delayed further downstream for the double suction case. This behaviour may indicate a modification of the characteristics of the boundary layer.

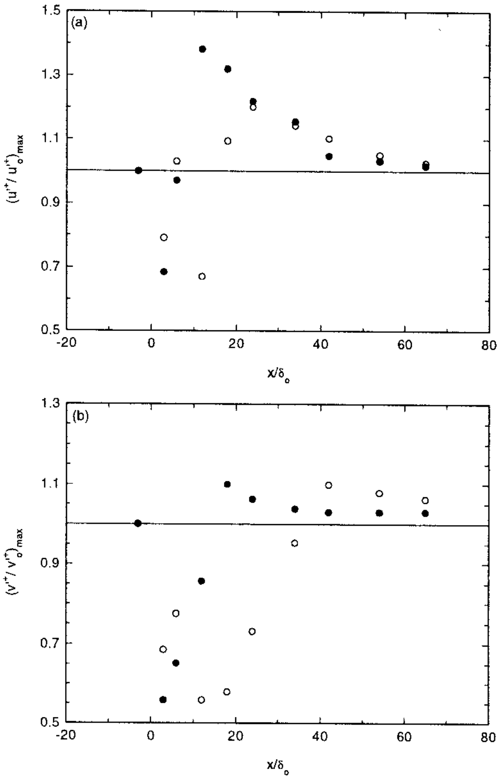

Fig. 7. Streamwise variation of (a) $(u'^+/u_o'^+)_{max}$, (b) $(v'^+/v_o'^+)_{max}$. Open symbols, two strips; closed symbols, one strip.

Figure 8 shows the distribution of w'^+. As one may expect it, the use of a double suction strips appears to accentuate the effect the single suction strip has on the spanwise velocity fluctuation.

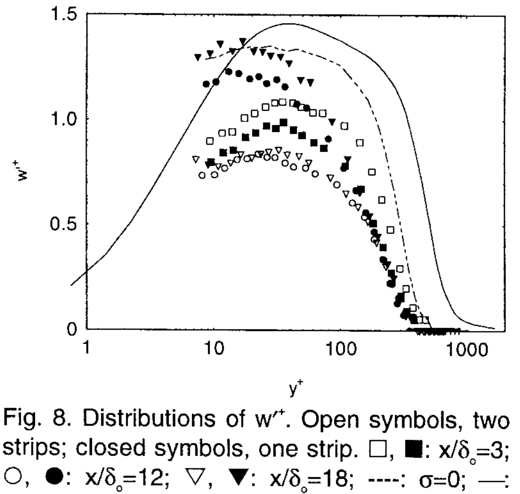

Fig. 8. Distributions of w'^+. Open symbols, two strips; closed symbols, one strip. □, ■: $x/\delta_o=3$; ○, ●: $x/\delta_o=12$; ▽, ▼: $x/\delta_o=18$; ----: $\sigma=0$; —: Spalart.

Altogether, the behaviour of u'^+, v'^+ and w'^+ may suggest a possible alteration of the mechanism responsible for the distribution of the turbulent kinetic energy among the difference normal stresses. Notice the absence of an overshoot in the distributions of w'^+, which constrasts with the u'^+ and v'^+ distributions. The reduction of $\langle w'^+\rangle$ in the near-wall region is consistent with the idea that suction has a stabilising effect in the spanwise direction in that region (Djenidi and Antonia, 2001) which is corroborated by the flow visualisation of Djenidi et al. (2002). This stabilisation may result in a weakening of the near-wall streamwise vortices, which in turn could lead to a skin friction reduction.

CONCLUSIONS

The effect of suction applied through a pair of porous wall strips on a turbulent boundary layer has been examined with the use of hot-wire anemometry. The results indicate that the use of a second strip increases the total skin friction reduction relative to one suction strip. Furthermore, the use of two strips not only extends the relaminarisation zone but also reduces the overshoot in the longitudinal and normal rms velocities. While the minimum rms occurs at $x/\delta_0 = 3.0$ for one strip and $x/\delta_0 = 12$ for two strips, the reduction observed for the latter case is larger. The extended streamwise distance over which the reduction of C_f occurs may reflect the effect suction has on the large-scale structures. This effect is enhanced with two suction strips because the second strip acts on a boundary layer whose Reynolds number has been reduced by the first strip and whose near-wall active motion has been weakened significantly.

AKNOWLEDGEMENT

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