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Influence of localised double suction on a turbulent boundary layer

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Abstract

The effects of localised suction applied through a pair of porous wall strips on a turbulent boundary layer have been quantified through the measurements of mean velocity and Reynolds stresses. The results indicate that the use of second strip extends the pseudo-relaminarisation zone but also reduces the overshoot in the longitudinal and normal r.m.s. velocities. While the minimum r.m.s. occurs at $x/\delta_o = 3.0$ (one strip) and $x/\delta_o = 12$ (two strips), the reduction observed for the latter case is larger. Relative to no suction, the turbulence level is modified by suction and the effect is enhanced with double suction. This increased effectiveness reflects the fact that the second strip acts on a boundary layer whose near-wall active motion has been seriously weakened by the first strip.

Keywords: Turbulence; Boundary layer; Suction; Relaminarisation

1. Introduction

For the past years, considerable effort have been devoted to the investigation of the application of suction applied either through open slit or porous wall strip for the purpose of skin friction drag reduction or for the control of the boundary layers [e.g. Sano and Hirayama (1985); Antonia et al. (1988, 1995); Oyewola et al. (2001); Pailhas et al. (1991); Merigaud et al., (1996)]. The interesting result that emerged is that suction could be used for controlling the flow, in particular for delaying transition and separation (Gad-el-Hak, 1989, 1998). Fundamentally, it has been shown that turbulence intensities respond less quickly to a change in boundary condition as compared to mean velocity, suggesting a dynamic change in the near-wall structures (Antonia et al., 1995; Oyewola et al., 2003). Quite a number of the past studies have focussed on the effect of the suction applied at low suction rates on a turbulent boundary layer, with the exception of Antonia et al. (1995). Antonia et al. (1995) studied the effect of concentrated wall suction, applied through a short porous wall strip, on a low Reynolds number turbulent boundary layer. They showed that, when the suction rate is sufficiently high, relaminarisation occurred almost immediately downstream of the suction strip. Further downstream, transition occurs followed by a slow return to a fully turbulent state. Furthermore, Oyewola et al. (2001, 2003) extended the work of Antonia et al. (1995) and found that both the suction rate, σ, and the momentum thickness Reynolds number, R_θ, played an important role in the relaminarisation process. They argued that the ratio $R_{\theta o}/\sigma$ (θ_o is the momentum thickness of the boundary layer at the leading edge of the porous strip when $\sigma = 0$) should

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not exceed a (as yet undetermined) critical value if relaminarisation is to occur. They also suggested that the re-transition, which follows the relaminarisation, could be controlled. They proposed that a series of suction strips could produce an effective means for controlling both the relaminarisation and the re-transition. Oyewola et al. (2004) exploited this latter suggestion, and found that the use of a second strip increases the total skin friction over one strip, and also extends the relaminarisation zone. The latter study was not sufficiently wide in scope to assess the response of a turbulent boundary layer to a concentrated wall suction applied through two successive porous strips, because only skin friction and energy balance were discussed.

The main aim of the present work, which extends that of Oyewola et al. (2001, 2003, 2004), is to quantify the effect of concentrated wall suction applied through a pair of porous strips on a turbulent boundary layer. The second strip is placed at a streamwise location where local recovery from the upstream suction strip first begins (Oyewola et al., 2004). Results for the mean velocity, Reynolds stresses, correlation coefficient, structural parameter and higher-order moments at various stations downstream of the suction strips are presented. They are compared with those obtained when suction is applied through the first suction strip only.

2. Measurement 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 (Fig. 1) through a two-stage two-dimensional (2-D) diffuser into the $1.6 \times 0.9\,\mathrm{m}^2$ 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-D contraction. A turbulent boundary layer developed on the floor of the rectangular working section (see schematic arrangement of the working section in Fig. 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

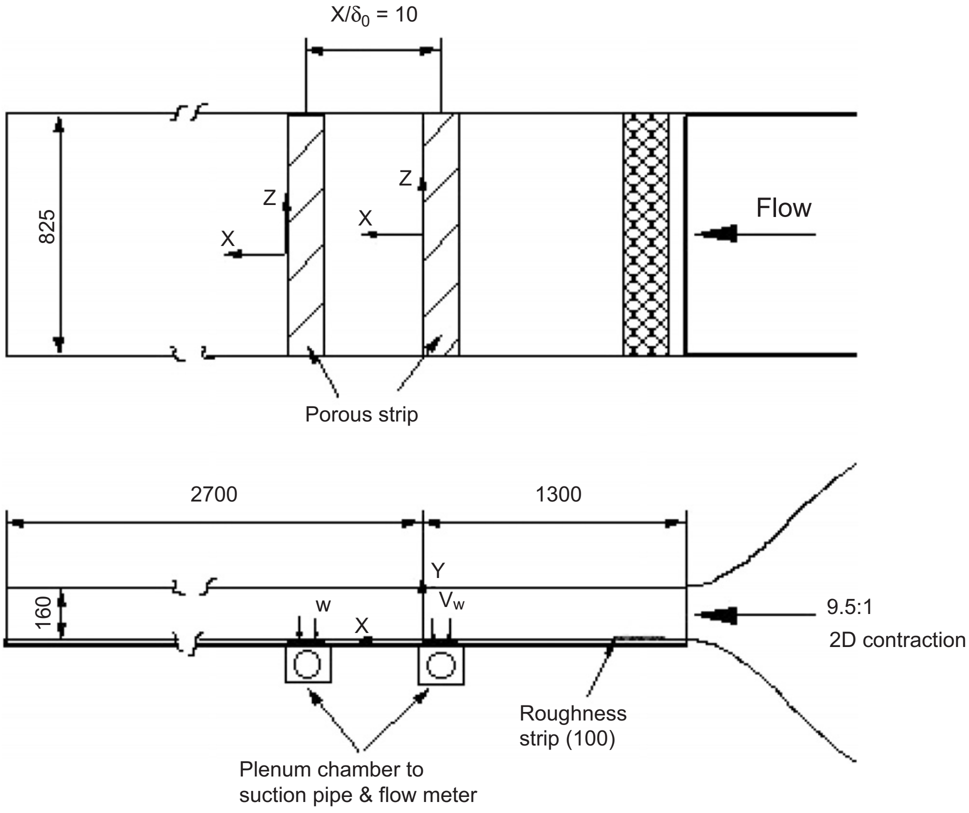

Fig. 1. Schematic arrangement of the working section.

streamwise locations. There were no systematic spanwise variations (maximum deviation was within $\pm 4\%$ of the centreline velocity).

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)$\nu/U_{\tau o}$ (where $U_{\tau o}$ is the friction velocity with no suction and ν is the kinematic viscosity) were 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 $\pm 3\%$.

The second porous strip is placed at a streamwise location of $x/\delta_o \approx 10$; δ_o is the boundary layer thickness at the leading edge of the first strip without suction, this value being 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, 2003). The free-stream velocity U_1 is 3.25 m/s and the corresponding initial momentum thickness Reynolds number $R_{\theta o}$ ($\equiv U_1\theta_o/\nu$, where θ_o is the momentum thickness at the leading edge of the first suction strip when no suction is applied) is 750. The suction rate σ ($\equiv V_w b/\theta_o U_1$, 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 strip only. The combined suction (volumetric) flow rate 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 with a MKS Baratron pressure transducer; the output of this instrument was averaged after digitising at 400 Hz for approximately 120 s. A propagation-of-error analysis indicated that the uncertainty in the measurement of skin friction was about $\pm 5\%$. This was estimated by measuring the skin friction 10 times, using records of about 60 s in each case, at several streamwise locations downstream of the strips. At each location, the uncertainty was $\pm 5\%$ of the mean value. A better approach in determining the skin friction is to use the hot-wire method, although it is much more time-consuming. Measurements of the mean velocity and velocity fluctuations were carried out with single and crossed hot-wire probes operated with 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 no-suction Reynolds number based on the sensor length, $l_o^+ = lU_{\tau o}/\nu$ (l is the length of the wire), was in the range 4–6 (hereafter the superscript + will denote normalisation by wall variables, i.e. the friction velocity and kinematic viscosity). The analogue 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 $\pm 0.5\%$) of mean velocity and velocity fluctuations.

3. Mean velocity and Reynolds stresses

Distributions of the mean velocity, U^+, are shown in Fig. 2(a and b) for one and two strips, in terms of y^+ for different streamwise stations downstream of the porous strips. Also shown in the figure are the Blasius distributions. Results for $\sigma = 0$ are shown in both cases in order to provide a reference against which the effect of suction can be assessed. Despite the small value of $R_{\theta o}$ (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) (not shown here). The data collapse onto the no-suction profile in the region below $y^+ \leqslant 10$, highlighting the rapid response of the mean velocity to a change in boundary condition. The scatter of some of the data sets in this region, especially for $y^+ < 5$ is partially due to heat conduction into the wall from the hot wire. 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 $x/\delta_o = 42$. This is consistent with the C_f distribution (Oyewola et al., 2004). The U^+ distributions with two strips show 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 strip. With one strip, recovery starts at about $x/\delta_o \approx 12$, whereas it begins at x/δ_o in the range 18–24 when two strips are used. Nonetheless, in each case, the profiles return to the undisturbed profile at $x/\delta_o = 65$.

The streamwise evolutions of the ratio of the r.m.s. of the longitudinal velocity fluctuations and the local mean velocity (u'/u) viz turbulence levels, are shown in Fig. 3. While the ratio reaches 0.37 near the wall for no-suction case, it changes significantly for both cases of suction as x/δ_o increases. For example, the ratio reaches minimum value of 0.22 at $x/\delta_o = 3$ for single suction, and 0.18 at $x/\delta_o = 12$ for double suction. The reduction of the turbulence levels relative to the no-suction case persists to $x/\delta_o = 18$ for two strips as compared with $x/\delta_o = 6.2$ for those of one strip. These changes in the turbulence levels by suction may suggest a modification in the near-wall structures. It should be noted

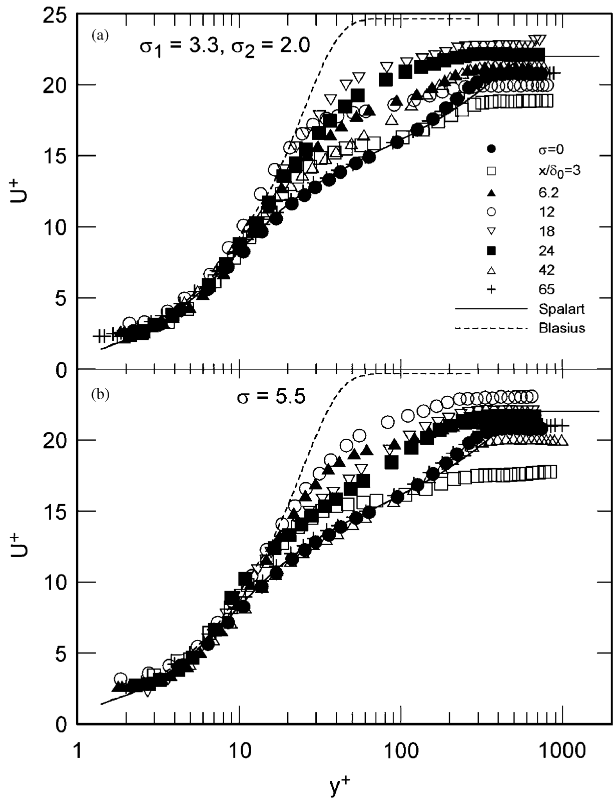

Fig. 2. Mean velocity distributions for (a) two strips, (b) one strip.

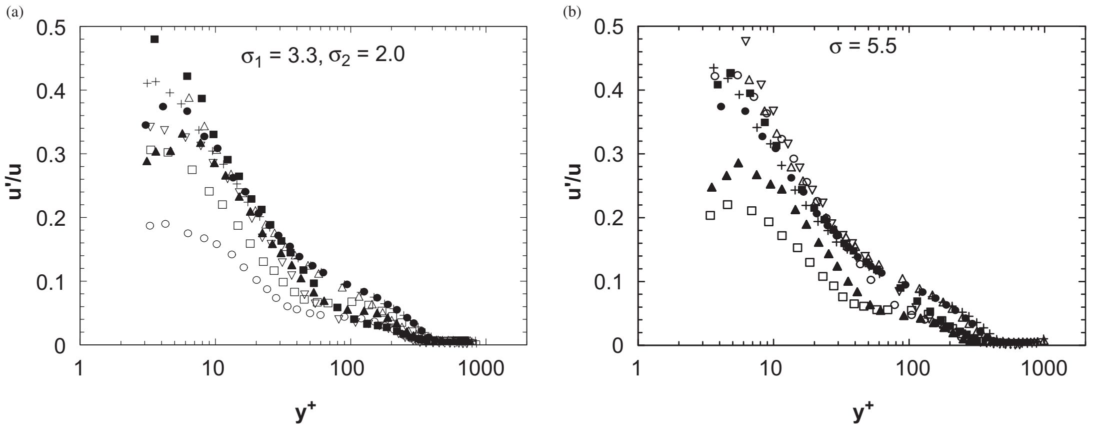

Fig. 3. Streamwise variation of u'/u for (a) two strips, (b) one strip.

that since turbulence levels are not Reynolds-number dependent (Fernholz and Finley, 1996); the changes observed when suction is applied may not be attributed to a reduction in the Reynolds number but rather suggest the interference of suction with the mechanism of the boundary layer. The effect is enhanced with two strips *vis-à-vis* one strip.

The streamwise variations of the r.m.s. values of the longitudinal (u'^{+}), transverse (v'^{+}), and spanwise (w'^{+}) velocity fluctuations, and of the Reynolds shear stress ($-\langle u^{+}v^{+}\rangle$) are shown in Figs. 4 and 5 for two strips and one strip, respectively. In general, the r.m.s. and Reynolds shear stress magnitude with the two strips are significantly lower than those for one strip in the region $12 \leqslant x/\delta_o < 42$, highlighting the cumulative effect of the two strips. Comparison between

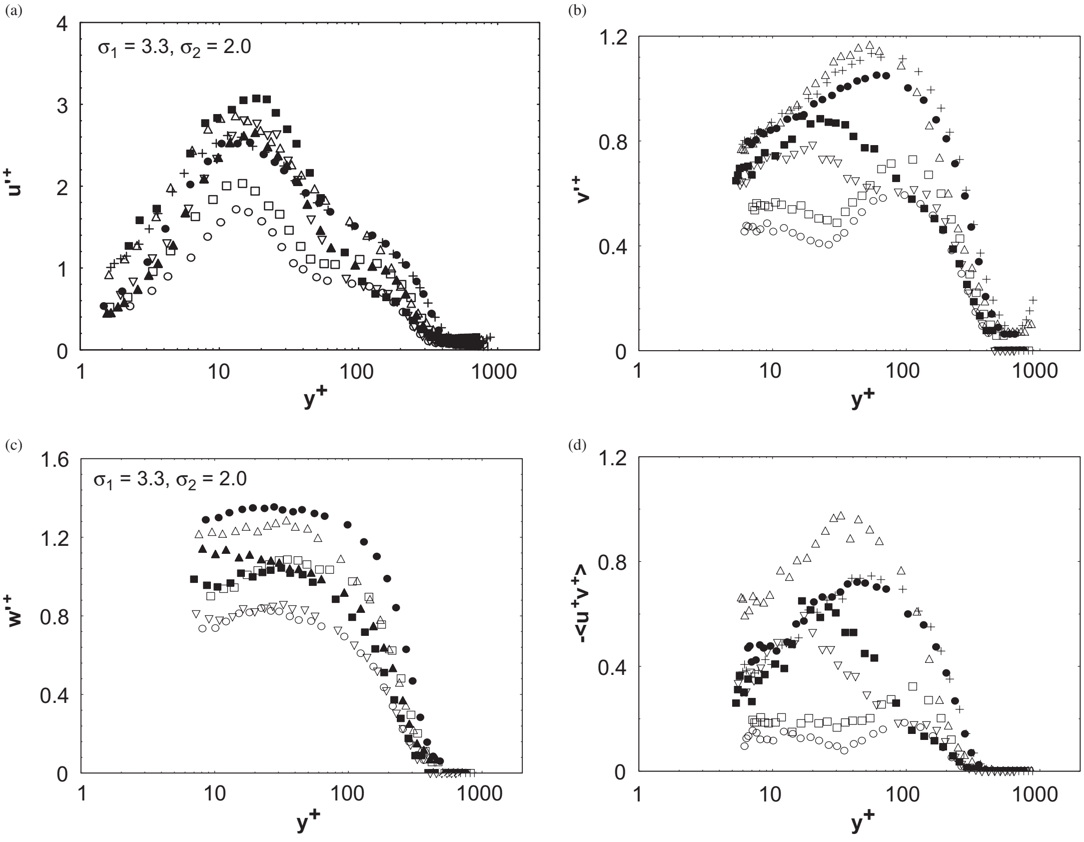

Fig. 4. Streamwise variation of (a) u'^{+}; (b) v'^{+}; (c) w'^{+}; (d) $-\langle u^{+}v^{+}\rangle$ for two strips. All symbols are as in Fig. 2.

the Reynolds stress distributions for the two suction cases reveals differences in the response of the individual Reynolds stresses. For example, at $x/\delta_o = 24$ the u'^{+} distributions are almost similar for both the single and double strips, while the distributions for v'^{+} and $\langle u^{+}v^{+}\rangle$ for the two strips are considerably different (shifted downward) from those for the single strip. This clearly highlights and corroborates the argument of Antonia et al. (1995), i.e. that the recovery proceeds at different rates between the different Reynolds stresses: u'^{+} appears to be the quickest to recover. The two strips, while altering the individual rates of recovery, do not change the relative order of recovery between the Reynolds stresses. The second strip acts in a relatively similar manner to the first on a turbulent field weakened by the latter. Note how, for $x/\delta_o \geqslant 12$, the distributions with the second strip active are significantly reduced when compared to those with only the first strip. This indicates that the effect of the second suction rate not only adds to the first suction effect; it (i) extends it, allowing the postponement of the recovery of the layer, and (ii) "intensifies" it, further reducing the skin friction. The reduction of the Reynolds stresses may suggest a weakening of the active motion and, to a lesser degree, the inactive motion. The weakening of the active motion is expected to result in an alteration of the momentum transfer in the near-wall region as it can be inferred from the significant reduction of $-\langle u^{+}v^{+}\rangle$. The second suction further weakens this motion. The streamwise evolutions of the turbulent kinetic energy for two strips and one strip are shown in Fig. 6. The cumulative effect of the suction applied through two strips is evidence in the region $12 \leqslant x/\delta_o < 24$ as compare with those of one strip. The data show considerable reduction relative to the no-suction case. The reduction suggests a possible alteration in the redistribution of the turbulent kinetic energy among the Reynolds stresses. This would lead to structural changes in the boundary layer due to the weakening of the near-wall structure. The structural change would be more pronounced downstream of the second strip.

As one may expect, the use of two strips appears to accentuate the effect the single suction strip has on the spanwise velocity fluctuation. Overall, the relative behaviour of u'^{+}, v'^{+} and w'^{+} suggest a possible alteration of the mechanism responsible for the distribution of the turbulent kinetic energy among the different normal stresses. There is no overshoot in the distributions of w'^{+}, in contrast with the u'^{+} and v'^{+} distributions. The reduction of w'^{+} in the

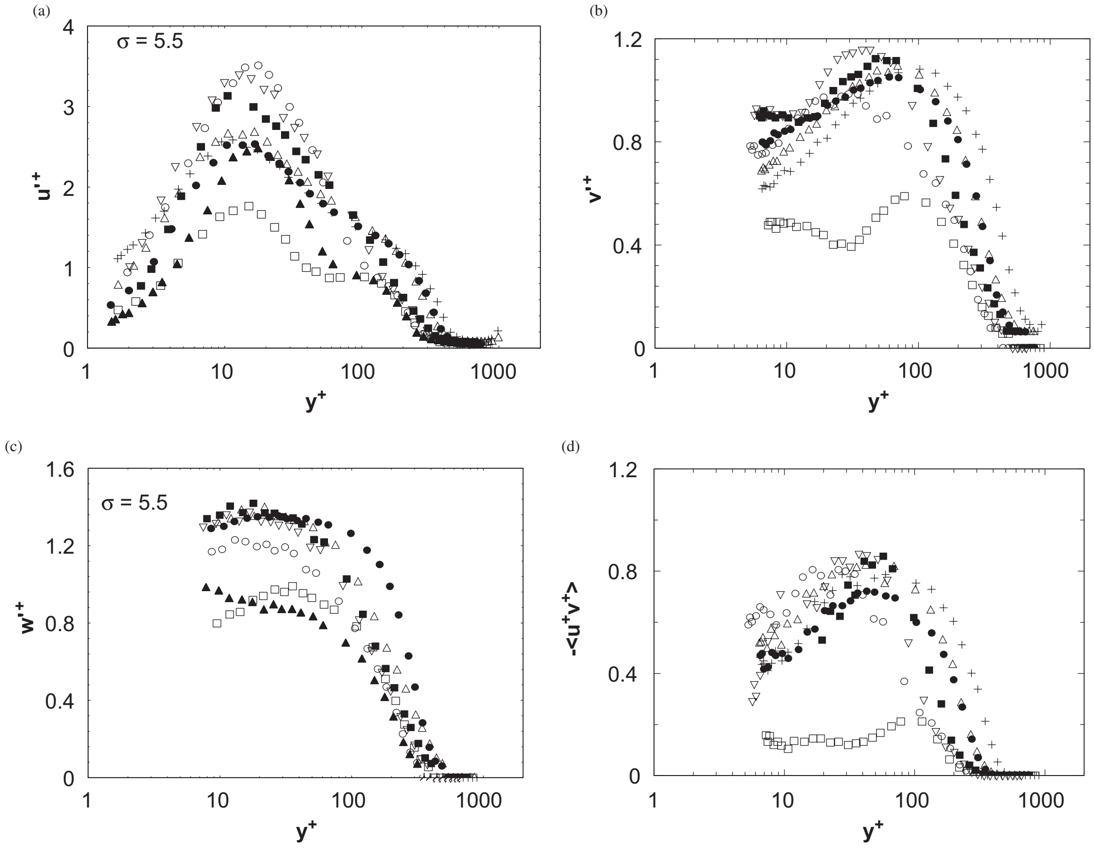

Fig. 5. Streamwise variation of (a) u'^+; (b) v'^+; (c) w'^+; (d) $-\langle u^+v^+\rangle$ for one strip. All symbols are as in Fig. 2.

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) and was corroborated by the flow visualisations 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 reduction in skin friction as observed by Oyewola et al. (2004).

One consequence of using two strips is the observed overshoot in u'^+. This latter quantity is significantly reduced, suggesting that the layer has been dynamically weakened. A practical application of this would be to have a series of suction strips acting successively on a continuously weakened turbulent boundary layer so that relaminarisation could be achieved gradually. Fig. 7 shows the streamwise variations of the maximum values of u'^+, v'^+, normalised by the unperturbed counterpart values. First, an oscillation of both quantities is observed. Second, after introducing the second strip, the amplitude of the oscillation is reduced. With two strips, the overshoot observed in u'^+ and v'^+ was reduced and delayed further downstream. It would seem that the characteristics of the boundary layer have been modified in a significant manner.

4. Correlation coefficient and structural parameter

Streamwise variations of the correlation coefficient R_{uv} $(= -\langle u'v'\rangle/(\sqrt{\langle u'^2\rangle}\sqrt{\langle v'^2\rangle}))$, which is a measure of the extent of correlation between u and v fluctuations are plotted in terms of y/δ in Fig. 8 for single and double suction. Interestingly, the maximum value of R_{uv} at $\sigma = 0$ is constant in all the streamwise locations and is around 0.45, which is in close agreement with the generally accepted value for a zero pressure gradient turbulent boundary layer. For both suction cases at $x/\delta_o = 3.0$, R_{uv} decreases ($y/\delta < 0.2$), slightly increases ($0.2 < y/\delta < 0.7$), and decreases significantly in the other part of the boundary layer when suction is applied. However, downstream of the second strip, R_{uv} decreases in every part of the boundary layer. The reduction of R_{uv} is closely related to the decrease of $\langle u'v'\rangle$ in the near-wall

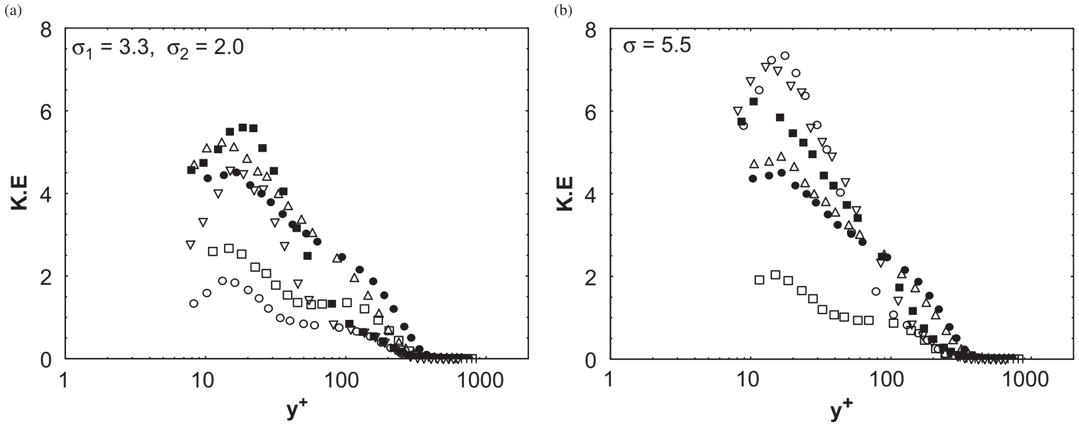

Fig. 6. Streamwise variation of turbulent kinetic energy K.E. for (a) two strips (b) one strip. All symbols are as in Fig. 2.

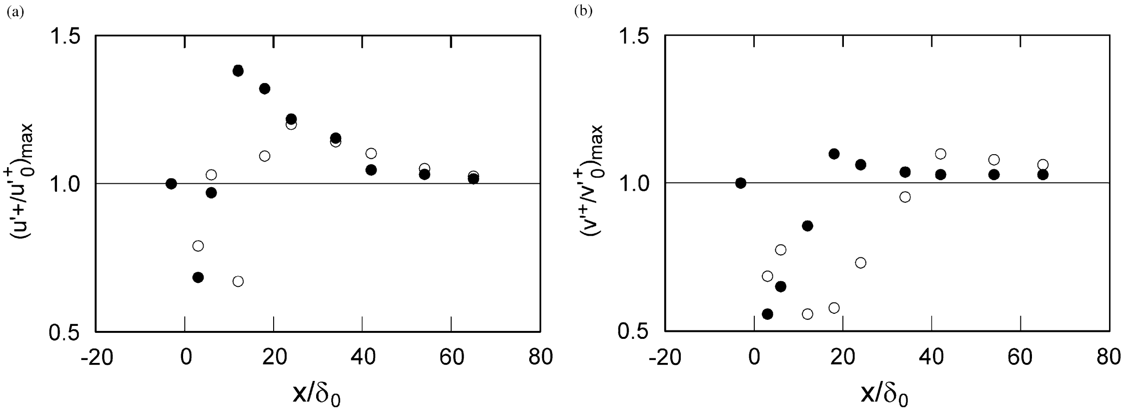

Fig. 7. Streamwise variation of (a) $(u'^+/u_o'^+)_{\max}$ and (b) $(v'^+/v_o'^+)_{\max}$. Open symbols, two strips; closed symbols, one strip.

region, and emphasised the strong decorrelation between u and v fluctuations. The reduction may suggest a structural change in the layer. The result would indicate that the changes are more pronounced for double suction. Also, the alteration of R_{uv} would provide further support for the weakening of the near-wall quasi-coherent structure, which in turn would cause a decrease in the skin friction, as observed by Oyewola et al. (2004).

The previous result suggests a structural change in the boundary when suction is applied. This is confirmed in Fig. 9, which shows the distributions of the structural parameter $a_1(=-\langle uv\rangle/\langle q^2\rangle$, where $\langle q^2\rangle = \langle u^2\rangle + \langle v^2\rangle + \langle w^2\rangle)$. The distributions of the zero-suction data show that a_1 is nearly constant over a large fraction of the boundary layer, with an approximate value of 0.14, which is in reasonable agreement with the value deduced by Bradshaw (1967) from the measurements of Klebanoff (1955). In the vicinity of the first strip, a_1 decreases slightly in the near-wall, but decreases significantly at the other parts of a boundary layer when suction is applied. The reduction is more pronounced for the double suction than the single suction downstream of the second strip. This is not surprising, since 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. The result may suggest a further weakening of the near-wall active motion, which contributes significantly to the momentum transfer. The reduction is consistent with the effect of double suction observed on the normal stresses, and shear stress in Fig. 4. Thus, the reduction of a_1 relative to no suction, may suggest an alteration in the efficiency of turbulence in generating shear stress. This implies that, with suction, shear stress (momentum transfer) would possibly decrease more than the turbulent energy downstream of the strip. This argument is consistent with the significant reduction observed in $\langle u^+v^+\rangle$ more than the other Reynolds stresses. The effect is enhanced with double suction.

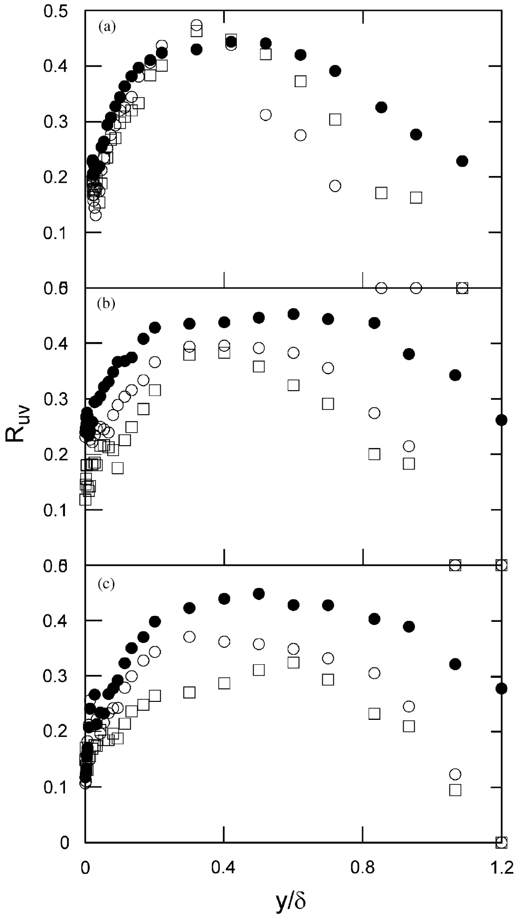

Fig. 8. Streamwise variations of the correlation coefficient R_{uv}. (a) $x/\delta_o = 3$, (b) $= 12$, and (c) $= 18$. ●: $\sigma = 0$; ○, single suction; □, double suction.

5. Higher-order moments

While the previous results of mean velocity and Reynolds stresses distributions revealed that near-wall coherent structures are significantly altered when suction is applied through two strips than one strip, the measurements of the higher-order moments should provide further quantification of the structural changes of the boundary layer, since they are expected to be more sensitive to any changes in boundary conditions than the second-order moments. Fig. 10 shows the streamwise variation of $\langle u^{+2}v^{+}\rangle$, $\langle v^{+3}\rangle$ and $-\langle v^{+2}u^{+}\rangle$ plotted in the inner scaling for suction applied through two strips and one strip. Also shown in the figure is the data for $\sigma = 0$ for comparison with the suction data. Downstream of the first strip ($x/\delta_o = 3$), the suction data depart significantly from their no-suction counterpart. The attenuation may suggest a manipulation of the organised motion responsible for the turbulent transport within the boundary layer. The inner peak which is larger for $\sigma = 0$ is attenuated more than the outer peak. This is not surprising since the coherent structures are more dominant in the former; the reduction may provide further evidence of the weakening of the near-wall quasi-coherent structures. It is interesting to observe similar attenuation for both cases of suction at $x/\delta_o = 3$, suggesting that no further reduction is possible if the combination of σ exceeds a certain suction rate. This is consistent with the observations that relaminarisation can be achieved downstream of the suction strip for an appropriate combination of the suction rate and Reynolds number (Oyewola et al., 2003). The reduction in $\langle u^{+2}v^{+}\rangle$ and $\langle v^{+3}\rangle$ may indicate an alteration in the transport of u'^2 and v'^2, respectively, by v' velocity fluctuations. In other words, the attenuation in the near-wall region may suggest that the intensity of the wall-normal transport of the sublayer fluid has been interfered with, and it may give rise to a layer of reduced intensity. Also, since the normal gradient of u'^2v' is related to the spanwise vorticity fluctuation ω'_z in the near-wall region by the equation (Fernholz and

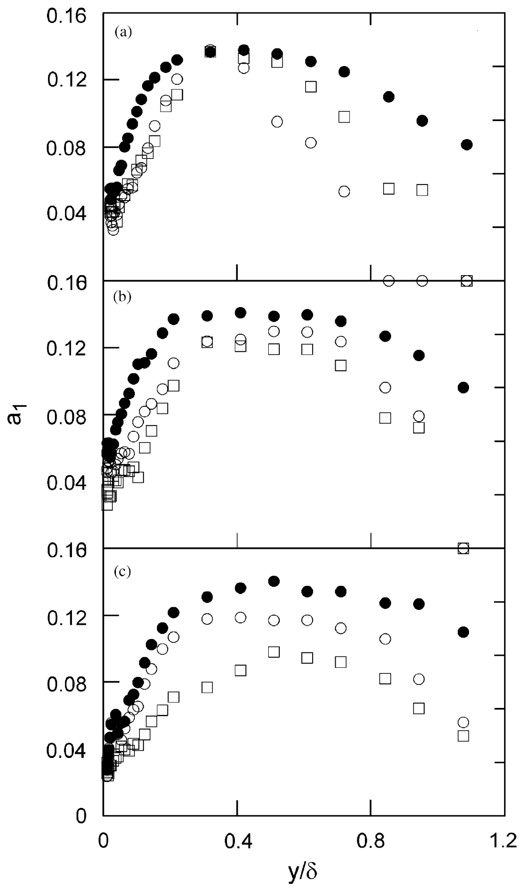

Fig. 9. Distributions of the structural parameter a_1. (a) $x/\delta_o = 3$, (b) $= 12$, and (c) $= 18$. Symbols are as in Fig. 7.

Finley, 1996):

$$-\partial(u'^2 v')/\partial y \approx 2u'v'\omega'_z - u'^2 \partial v'/\partial y,$$

the reduction in $\langle u^{+2} v^{+} \rangle$ may suggest indirect evidence of a weakening of the streamwise vortices, which in turn would result in the stabilisation of the near-wall flow. Meanwhile, the reduction observed in $-\langle v^{+2} u^{+} \rangle$ may suggest an alteration in the momentum transport of $-\langle uv \rangle$ by v' velocity fluctuations. While the attenuation at $x/\delta_o = 12$ is significant for the double suction, the single suction overshoot the corresponding undisturbed profile in the inner-region. For example, $\langle u^{+2} v^{+} \rangle$, $\langle v^{+3} \rangle$ and $-\langle v^{+2} u^{+} \rangle$ are reduced to as much as 60%, 90% and 40%, respectively, in their local inner peaks. The reduction is consistent with the fact that the second strip acts on the boundary layer whose Reynolds number has been reduced by the upstream suction (Oyewola et al., 2004) and whose near-wall motion has been interfered with. The reduction of $\langle v^{+3} \rangle$, more than the others, may provide strong support for the weakening of the active based motion, and may also indicate an alteration in diffusion energy.

Altogether, the above results suggest that the boundary layer undergoes some changes when suction is applied, at least in the immediate vicinity of the suction strips. This is evidenced by the behaviour of the skewness and flatness factors of u and v shown in Figs. 11 and 12. While for all cases, S_u is positive in the near-wall region, changes sign and become negative at larger y^+ for suction cases. The magnitude of S_u is larger for suction data than for no-suction data in the near-wall region, but is reduced significantly below the no-suction data after crossing zero. In addition, the distribution of S_v increases in the near-wall region (until a local peak is reached), decreases, and then, again increases significantly in the outer region. Relative to no-suction, the values of the suction data are larger throughout the boundary layer.

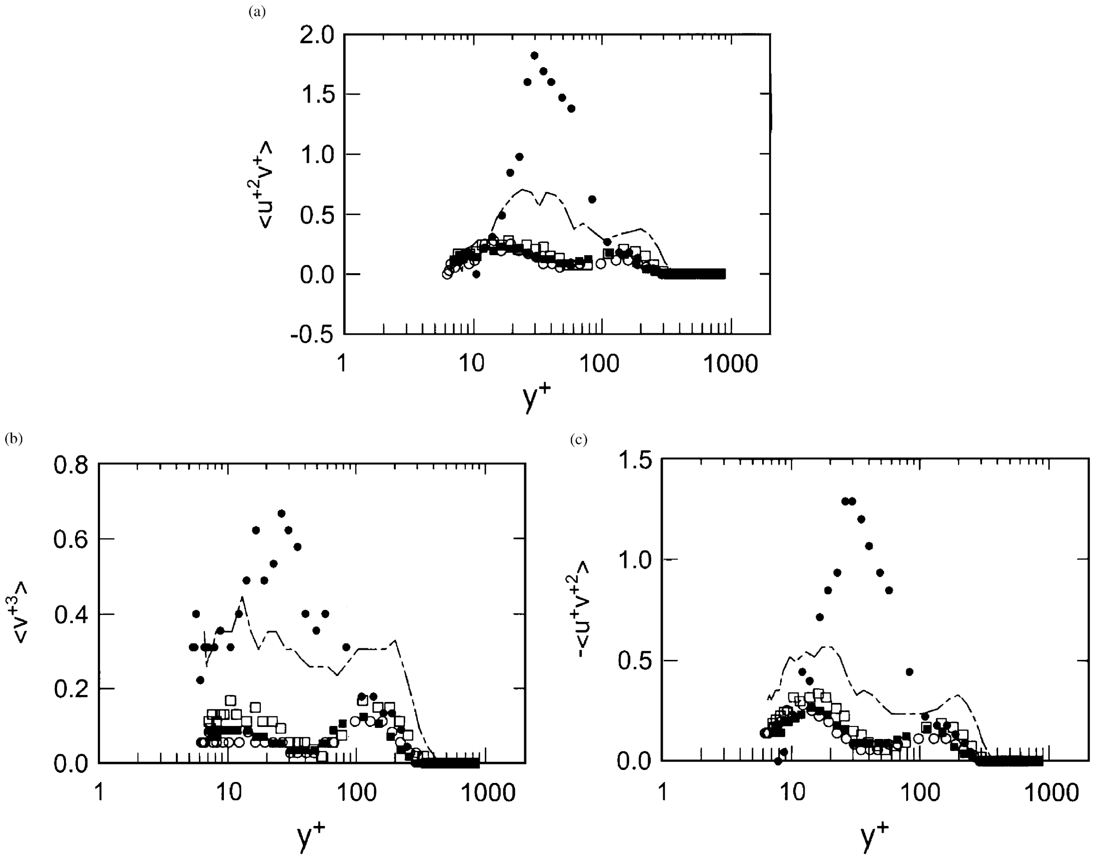

Fig. 10. Distributions of (a) $\langle u^{+2}v^{+}\rangle$, (b) $\langle v^{+3}\rangle$, and (c) $-\langle \mathrm{u}^{+}\mathrm{v}^{+2}\rangle$. Open symbols, two strips; closed symbols, one strip. □, ■, $x/\delta_o = 3$; ○, ●, $x/\delta_o = 12$; -----, $\sigma = 0$.

In both S_u and S_v, the behaviour is similar for the two cases of suction, and may suggest an alteration in the boundary layer structure. The results would indicate an alteration in the ejection ($u<0$, $v>0$) and sweep ($u>0$, $v<0$) activities in the near-wall region. This corroborates the suggestion that the eradication of the Reynolds shear stress is due to the mitigation/cessation of ejection of low momentum fluid and sweeps of high momentum fluids towards the wall (Antonia et al., 1995; Oyewola et al., 2003). The quadrant analysis of u and v fluctuations carried out by Zhu and Antonia (1995) supports this suggestion. The authors showed that ejections and sweeps are significantly reduced when suction is applied. In the outer layer, and for $y^+ > 100$, there is a systematic variation of both S_u and S_v with suction. The magnitude of these quantities is larger for suction than those for no suction.

The quantities F_u and F_v, which provide a measure of the large-scale intermittency, are shown in Fig. 12. The rather large values of the streamwise flatness F_u in the near-wall region relative to non-suction case may suggest that the velocity signal has a high internal intermittency. The large values in both F_u and F_v may indicate that sweep motions are more intermittent over the suction than no-suction. The large values of F_v near the wall for the suction as compared to zero-suction may suggest that intense v fluctuations may be associated with the intermittent ejections of fluid away from the wall. The overall results would suggest that boundary layer structures have been modified. Kline et al. (1967) and Kim et al. (1971) identified the skewness and flatness factors in connection with the width of the streak filaments, which are produced close to the wall and contribute significantly to the bursting process. The departure of these quantities from the no-suction case indicates that this process has been altered by suction resulting in changes in the near-wall structure of the layer. The data would indicate that the changes are similar for both suction cases. Interestingly, there is a shift in y^+ where skewness and flatness factors are maxima with relative to no suction. This suggests that the near-wall structures have undergone a dynamical change downstream of the suction strips.

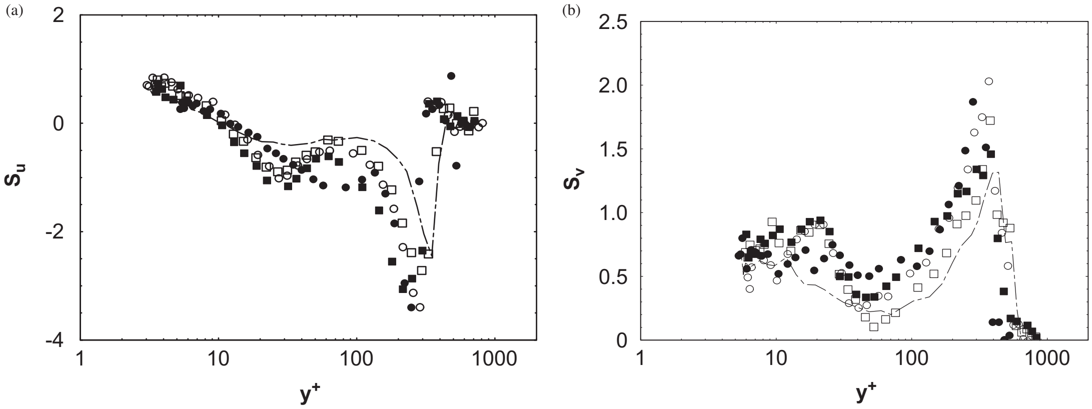

Fig. 11. Skewness of (a) u and (b) v. Open symbols, two strips; closed symbols, one strip. □, ■, $x/\delta_o = 3$; ○, ●, $x/\delta_o = 12$; - - - - -, $\sigma = 0$.

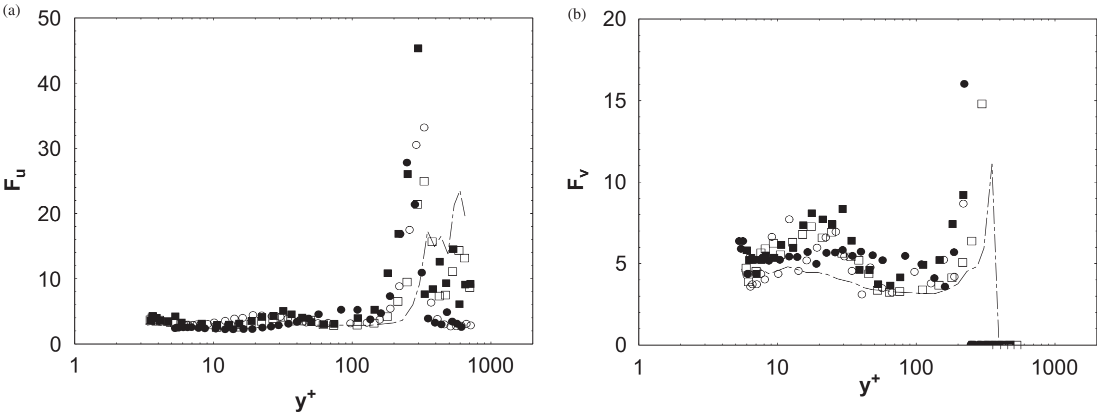

Fig. 12. Flatness of (a) u and (b) v. Open symbols, two strips; closed symbols, one strip. □, ■, $x/\delta_o = 3$; ○, ●, $x/\delta_o = 12$; - - - - -, $\sigma = 0$.

6. Conclusions

Hot-wire measurements have been made in a turbulent boundary layer subjected to localised wall suction, applied through a pair of porous strips, with the aim of examining the influence of double suction on the near-wall structure. Relative to the no-suction case, the use of second strip extends the pseudo-relaminarisation zone and also reduces the overshoot in the longitudinal and normal r.m.s. velocities. While the minimum r.m.s. occurs at $x/\delta_o = 3.0$ (one strip) and $x/\delta_o = 12$ (two strips), the reduction observed for the latter case is larger. The turbulence level is significantly reduced downstream of the suction strips, and the effect is enhanced with double suction.

Relative to no-suction, there is a structural modification in the near-wall coherent structure as reflected in the significant change in both correlation coefficient and structural parameter when suction is applied. The results were confirmed by the measurements of the higher-order moments. The data indicates that the change is more pronounced for the double suction. This increased effectiveness reflects the fact that the second strip acts on a boundary layer whose near-wall active motion has been seriously weakened by the first strip.

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