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INFLUENCE OF REYNOLDS NUMBER ON THE SUCTION EFFECT ON THE TURBULENT BOUNDARY LAYER STRUCTURES

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Abstract. *This paper considers the influence of Reynolds number on the effect suction has on a turbulent boundary layer, subjected to localised suction, applied through a short porous wall strip. Measurements of the correlation coefficient and structural parameter show an alteration of the near-wall structures when suction is applied. The streamwise extent decreasing as Reynolds number increases. Relative to no-suction case, the rms value of ω_z is significantly reduced in the near-wall region, this reduction increasing with the suction rate, σ. The magnitude and wavelength of the variation of the spanwise vorticity decrease as Reynolds number increases, suggesting intensification of the near-wall streamwise vortices.*

Keywords. *Turbulent, boundary layer, suction, structures, measurements.*

1. Introduction

It has been well established that organized structures in turbulent flows play an important role in turbulent transport (Cantwell (1981), Robinson (1991)). Interfering with the turbulence structure of turbulent flows occurring in various engineering applications is of significance importance and benefit. Such applications include transpiration cooling, chemical processing, drying, drag reduction of airfoils etc. However, the effect Reynolds number plays especially in wall bounded flows have been studied quite a number by several authors. For example, reviews of the Reynolds number effects in wall-bounded flows especially, for undisturbed boundary layer has been adequately reported (Gad-el-hak and Bandyopadhyay (1994), Smith (1994), Fernholz and Finley (1996)). The interesting result that emerged is the variation of both mean and turbulent quantities with Reynolds number.

The effect of suction on the boundary layers has been widely studied for the past decades, ranging from experimental to analytical work. The earlier work of Prandtl (1904) has reviewed by Schlichting (1965) on the used of suction on boundary layers in preventing separation provided a fundamental basis. Numerous works on laminar boundary layer confirmed that when suction is applied, the boundary layer becomes thinner, separation is delayed and stability increases. Sano and Hirayama (1985, 1985a, 1986) studied the effect of suction applied through a slit. Their results showed that while the mean flow and turbulence characteristics of the boundary layers are controlled by the suction flow rate, they are independent of suction velocities. Unfortunately, their measurements were only at the immediately vicinity of the suction slit. 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, pseudo-relaminarization occurred almost immediately downstream of the suction strip. Further downstream, transition occurs followed by a slow return to a fully turbulent state. During relaminarization, the measured skin friction coefficient C_f falls below the level corresponding to the no suction value. They found that recovery rate differs among the three Reynolds stress they measured: the longitudinal Reynolds stress $\langle u^2 \rangle$ is the first to return to the fully turbulent state, while the Reynolds shear stress $-\langle uv \rangle$ is the slowest to recover. Recently, Oyewola et al. (2003) extends the work of Antonia et al. (1995) and carried out experiments on the combined influence of the Reynolds number and localised wall suction on a turbulent boundary layer. They found that both the suction rate, σ, and the momentum thickness Reynolds number, R_θ played important role in the relaminarisation process. They argued that the ratio $R_{\theta o} / \sigma$ should not exceed a (as yet undetermined) critical value if relaminarisation is to occur.

The present study, which extends the work of Oyewola et al. (2003), focuses on the influence of Reynolds number on the suction effect on the turbulent boundary layer structures. This influence is quantifying through the measurements of correlation coefficient, structural parameter and spanwise vorticity downstream of the suction strip.

2. Measurements details

Experiments were carried out in a zero-pressure gradient two-dimensional turbulent boundary layer, which is subjected to concentrated suction, applied through a short porous strip. The turbulent boundary layer develops on the floor of the rectangular working section (Figure 1) after it is 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, which is about

1200 mm downstream of the roughness strip. Measurements were made at U_∞ of 3.25 and 7 ms^{-1}; the corresponding values of the initial momentum thickness Reynolds numbers $R_{\theta o}$ are 660 and 1400, respectively. A 3.25 mm thick porous strip with a width of 40 mm and made of sintered bronze with pore sizes in the range 40 – 80 μm or (0.4 – 0.9)ν/U_τ was mounted flush with the test section floor. Allowing for the width of the mounting recess step, the effective width (=b) of the strip was 35 mm. Suction was applied through a plenum chamber located underneath the suction strip and connected to a suction blower, driven by a controllable DC motor, through a circular pipe (internal diameter D = 130 mm and L/D ≈ 38, where, L, is the pipe length). The flow rate Q_r was estimated directly by radially traversing a Pitot tube located near the end of the pipe, for various values of the pipe centre-line velocity (U_c). A plot of Q_r vs U_c, allowed the suction velocity (V_w) to be inferred via the continuity equation ($Q_r = A_w V_w$, where, A_w is the cross-sectional area of the porous strip). The suction velocity 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%.

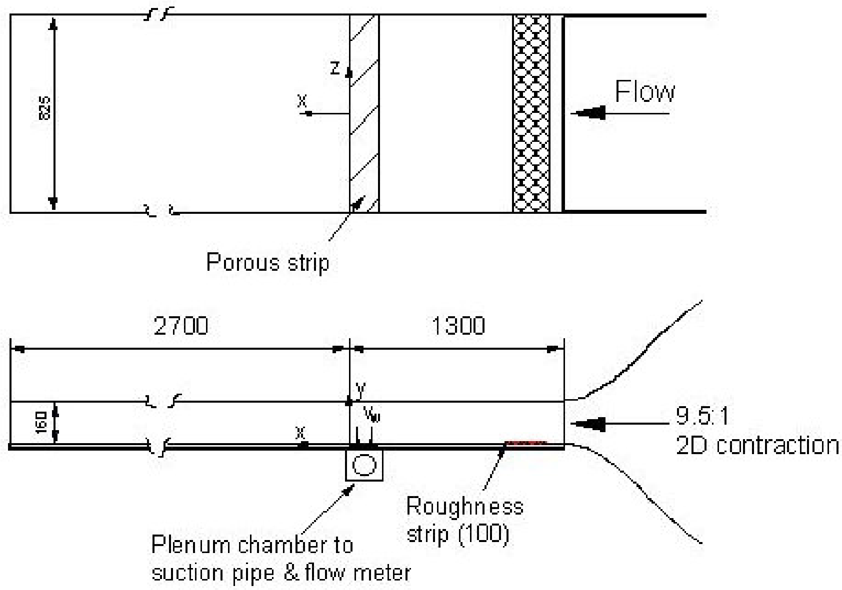

Figure 1: Schematic arrangement of the working section

Measurements were made for σ (normalised suction rate, severity index as introduced by Antonia et al., 1995 = $V_w b/\theta_o U_\infty$) = 0, 1.7, 3.3 and 5.5. The results at σ = 0 provided a reference against which the suction data could be appraised. The wall shear stress τ_w was measured with a Preston tube (0.72 mm outer diameter), and a static tube located approximately 35 mm above it at the same x position. The Preston tube was calibrated in a fully developed channel flow using a similar method to that described in Shah and Antonia, 1989 and Antonia et al., 1995. τ_w was determined from the relation τ_w = -h(dp/dx), where h is the channel half-width and p is the static pressure. Measurements of the velocity fluctuations in the streamwise and wall normal directions were made with cross wires, each inclined at 45° to the flow direction. 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 separation between the inclined wires was about 0.6 mm. Vorticity measurements were made with a probe comprising a cross-wire and two parallel hot-wires. The parallel single wires were orthogonal to the plane of the X-probe and located on either side of the centre of the X-probe (see Antonia and Rajagopalan (1990) for more details). The single wires were separated by a distance Δy = 1.1 mm (y is the normal direction to the wall), while the distance between the X-wires was about 1.23 mm. All hot wires were operated with in-house constant temperature anemometers at an overheat ratio of 1.5. The analog output signal of the hot wire was low pass filtered at 5kHz-8kHz, offset and amplified to within ±5 V. The performance of the vorticity probe was checked by comparing the velocity fluctuations with those measured using a single X-wire for the same flow conditions. The results (not shown here) showed reasonable agreement between the velocity fluctuations of the two measuring techniques. The uncertainty is less than 2%.

3. Correlation coefficient and Structural parameter

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 the Figures 2 and 3 for $R_{\theta o}$ = 660 and 1400 respectively. The maximum value of R_{uv} at σ = 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. Klebanoff (1955) obtained a correlation coefficient of about 0.5 over the entire region of the boundary layer. Senda et al. (1980) in their flat plate boundary layer with uniform injection obtained a similar value as Klebanoff (1955).

In the vicinity of the strip, R_{uv} decreases ($y/\delta < 0.2$), slightly increases ($0.2 < y/\delta < 0.7$), and decrease significantly in the other part of the boundary layer for all $R_{\theta o}$ when suction is applied. However, at $x/\delta_o = 9.1$, R_{uv} decreases in every part of the boundary layer. For example, relative to $\sigma = 0$, R_{uv} of $R_{\theta o} = 660$ reduces as much as 25% when $\sigma = 5.5$, as compared with 10% reduction in R_{uv} of $R_{\theta o} = 1400$ of the same σ. The reduction of R_{uv} is closely related to the decrease of $\langle u'v' \rangle$ in the near-wall region, and emphasized the strong decorrelation between u and v fluctuations. The reduction may suggest a structural change in the layer.

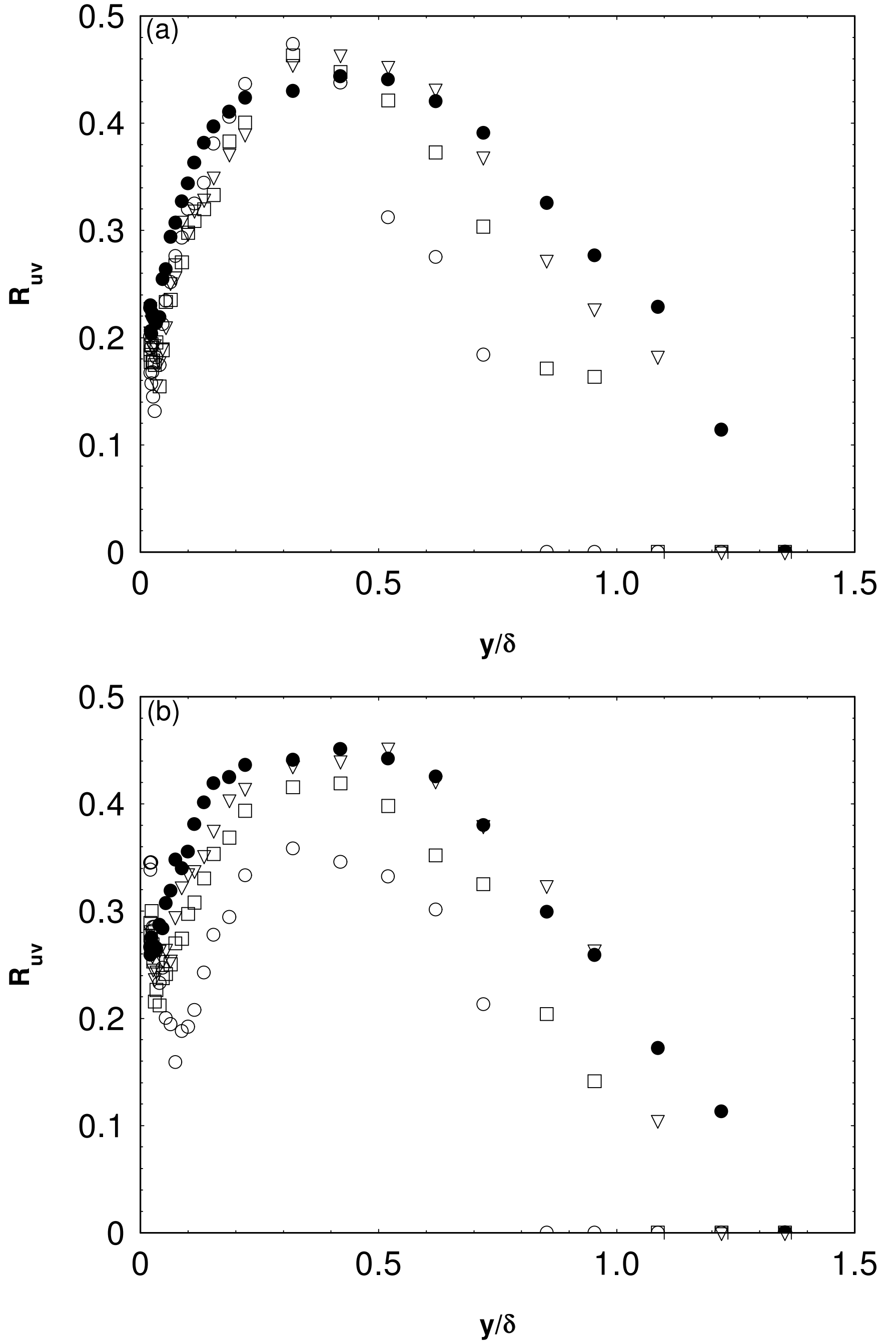

Figure 2: Streamwise variation of correlation coefficient for $R_{\theta o} = 660$. (a) $x / \delta_o = 3$; (b) 9.1, •: $\sigma = 0$; ∇: $\sigma = 1.7$; ♦ : $\sigma = 3.3$; o: $\sigma = 5.5$.

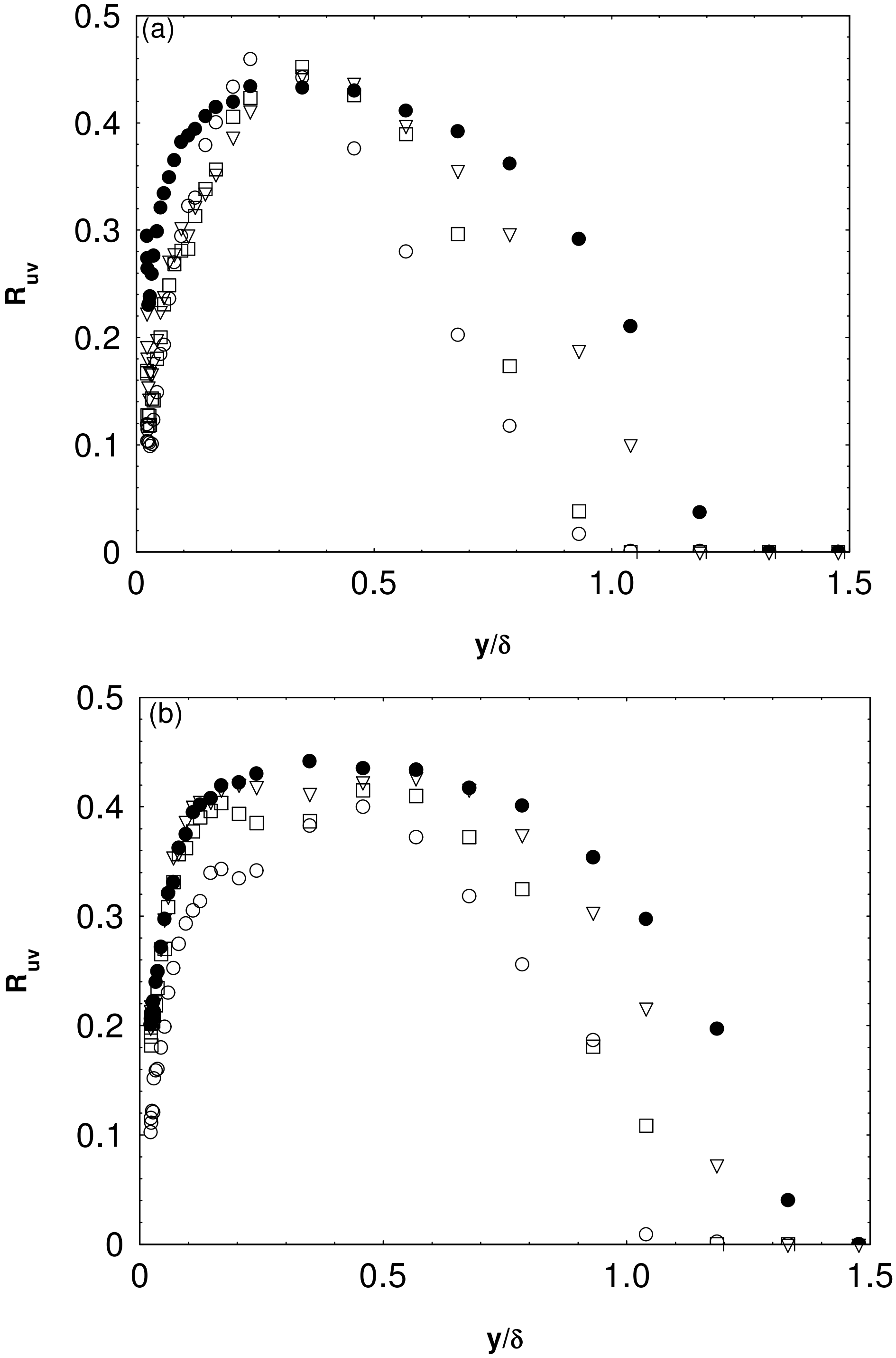

Figure 3: Streamwise variation of correlation coefficient for $R_{\theta o}$ = 1400. (a) x / δ_o = 3; (b) 9.1, •: σ = 0; ∇: σ = 1.7; ♦ : σ = 3.3; o: σ = 5.5.

The result would indicates that the changes are more pronounced for $R_{\theta o}$ = 660 and σ = 5.5. Also, the alteration of R_{uv} may 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. (2003). Gampert and Yong (1990) observed a similar reduction in R_{uv} in their drag reducing polymer solution. In the experiment of Merigaud et al. (1996) using slot suction, a reduction in R_{uv} was also observed but not as much as in the present data, partly due to difference in $R_{\theta o}$ and σ.

To assess further the influence of the Reynolds number on the effect suction has on R_{uv}, the streamwise variation of $(R_{uv} / R_{uv\ \sigma = 0})_{max}$ is plotted in Figure 4.9 for σ = 5.5. There is a dramatic change in the distribution in the region $0 < x/\delta_o < 40$, similar to that observed in the C_f / C_{fo} distribution (Oyewola et al., 2003). For example, while there is a sling drop in R_{uv} in the region $0 \leq x/\delta_o \leq 30$ at $R_{\theta o} = 660$, the magnitude of the drop reduces at $R_{\theta o} = 1400$, and occurs in the region $0 \leq x/\delta_o \leq 10$. The big decrease of R_{uv} at $R_{\theta o} = 660$ is consistent with a change in the near-wall structure of the layer. When $R_{\theta o} = 1400$, the change is less. This reflects the influence of the Reynolds number on the suction effects. A similar observation was drawn from the C_f measurements (Oyewola et al., 2003).

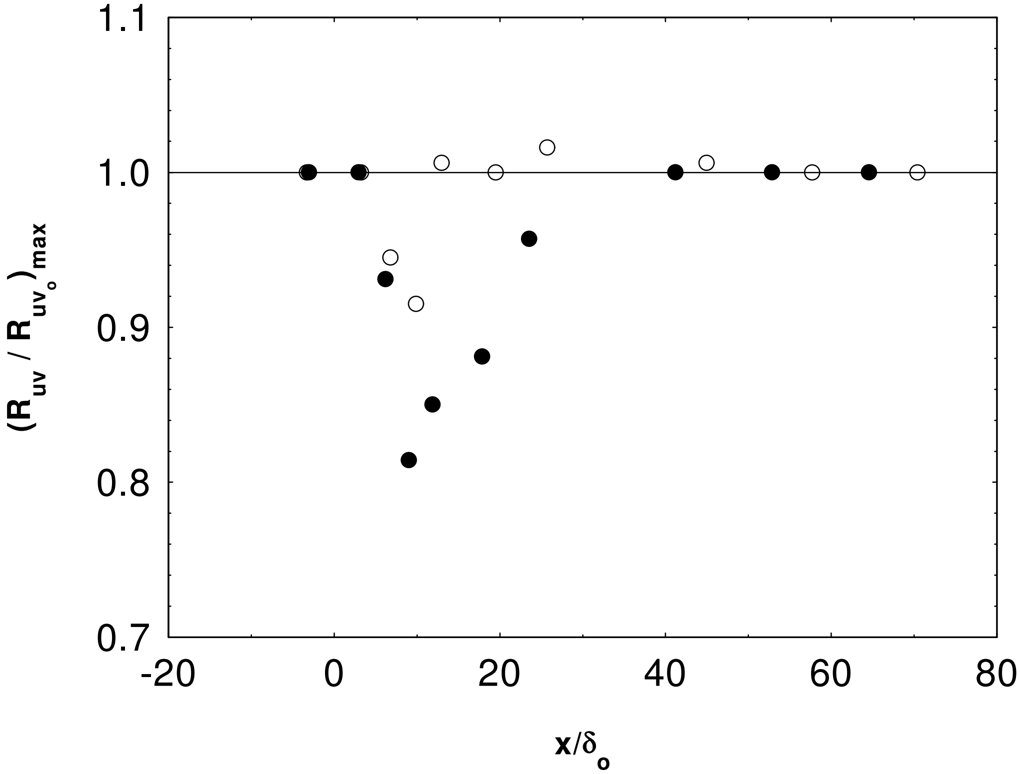

Figure 4: Streamwise variation of $(R_{uv} / R_{uv\ \sigma = 0})_{max}$ for $\sigma = 5.5$. Closed symbols $R_{\theta o} = 660$; open symbols, $R_{\theta o} = 1400$

The data suggested that the change in the near-wall structure would be more pronounced for $R_{\theta o} = 660$ than 1400. R_{uv} of $R_{\theta o} = 1400$ recovered quickly to the undisturbed $\sigma = 0$ with a slight overshoot ($x/\delta_o = 11.9$) as compared to the momentarily recovery of $R_{\theta o} = 660$ at $x/\delta_o = 40$.

The previous results suggest a structural change in the boundary layer when suction is applied. This is confirmed in the distributions of structural parameter a_1 ($= -\langle uv \rangle / \langle q^2 \rangle$, where $\langle q^2 \rangle = \langle u^2 \rangle + \langle v^2 \rangle + \langle w^2 \rangle$) shown in Figures 5 and 6 for $R_{\theta o} = 660$ and 1400, respectively. 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 strip, a_1 decreases slightly in the near-wall, but decreases significantly at the other part of the boundary layer when suction is applied. The reduction increases further downstream as σ increases, but reduces as $R_{\theta o}$ increases (Figures 6a and 6b). For instance, relative to $\sigma = 0$, a_1 decreases by 40% for $R_{\theta o} = 660$ and 10% for $R_{\theta o} = 1400$ when $\sigma = 5.5$ and $x / \delta_o = 9.1$. The reduction is consistent with the effect of σ observed on the normal-stresses, and shear stress. 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 decreases 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 decrease in the level of reduction of a_1 when $R_{\theta o}$ increases, would be explained by the intensification of the near-wall structures. Sano and Hirayama (1985) found that a_1 was equal to 0.15 and independent of suction flow rate. The present reduction of a_1 downstream of the strip, would indicate differences in σ and $R_{\theta o}$.

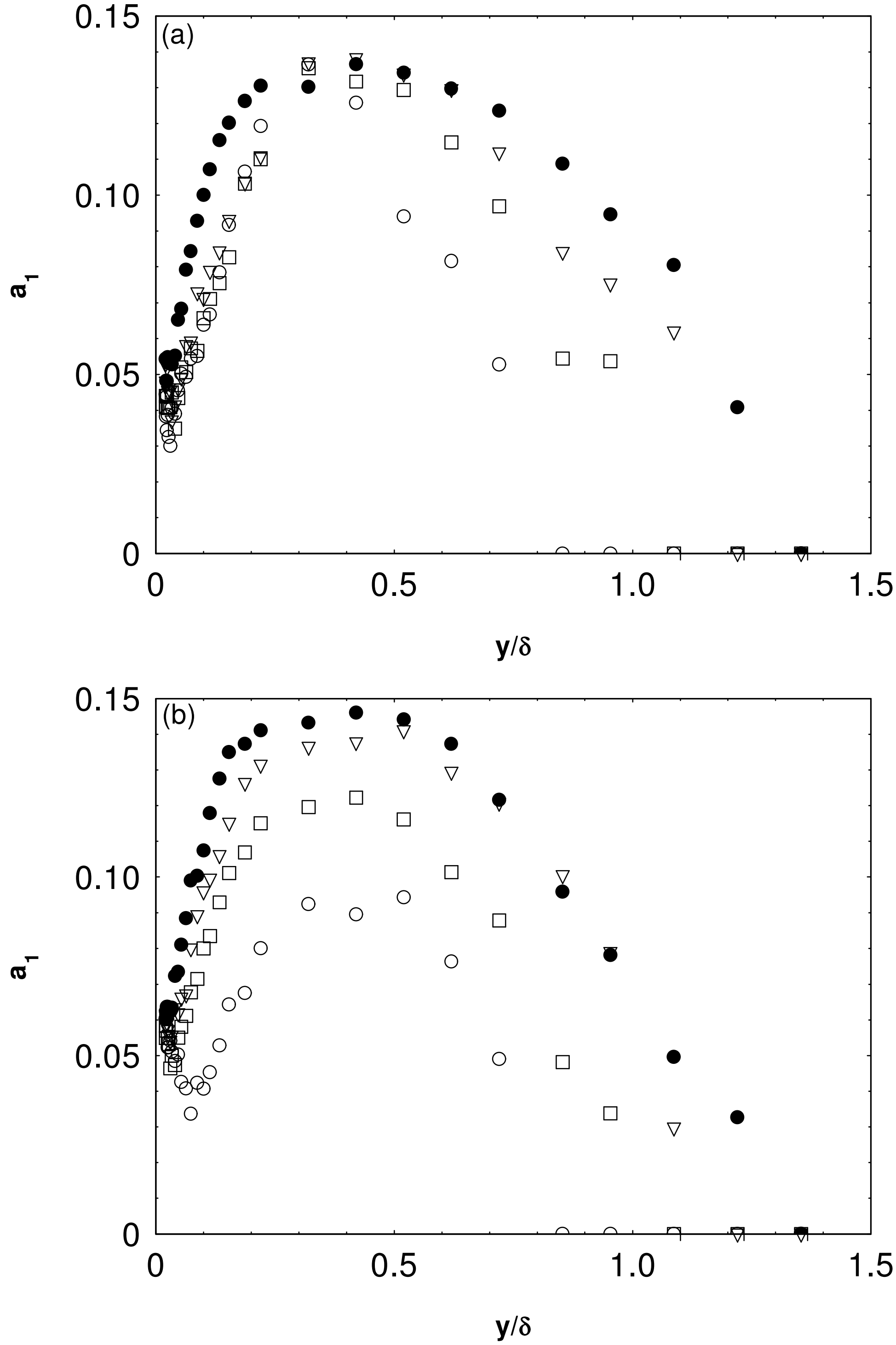

Figure 5: Streamwise variation of structural parameters for $R_{\theta o} = 660$. (a) $x / \delta_o = 3$; (b) 9.1, •: $\sigma = 0$; ∇: $\sigma = 1.7$; ♦ : $\sigma = 3.3$; o: $\sigma = 5.5$.

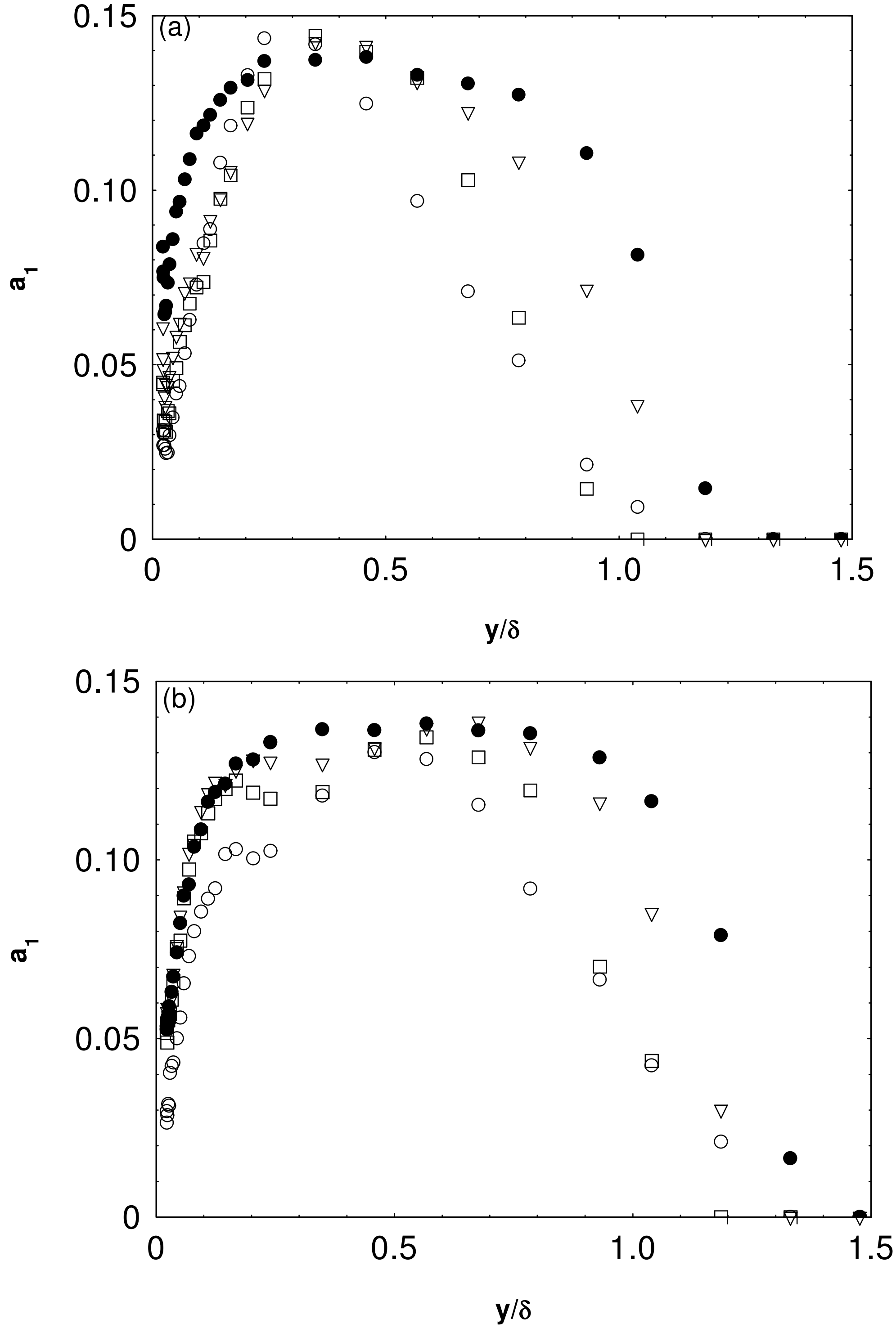

Figure 6: Streamwise variation of structural parameters for $R_{\theta o}$ = 1400. (a) x / δ_o = 3; (b) 9.1, •: σ = 0; ∇: σ = 1.7; ♦ : σ = 3.3; o: σ = 5.5.

4. Spanwise vorticity

While the previous results revealed that the near-wall coherent structures are altered when suction is applied, the measurements of the fluctuating spanwise vorticity should provide further quantification of the structural changes of the boundary layer. Figure 7 shows the distribution of the measured rms spanwise vorticity ω'^{+}_{z} ($\equiv \omega'_z \nu / U_\tau^2$) in the near-wall region. Also shown in the figure are the measured data of Rajagopalan and Antonia (1993), Klewicki and Falco

(1990), and the DNS data of Spalart (1988) at R_θ = 1400. The present non-suction data show a reasonable agreement with that of Rajagopalan and Antonia (1993) especially figure 7b, but lower than Klewicki and Falco (1990).

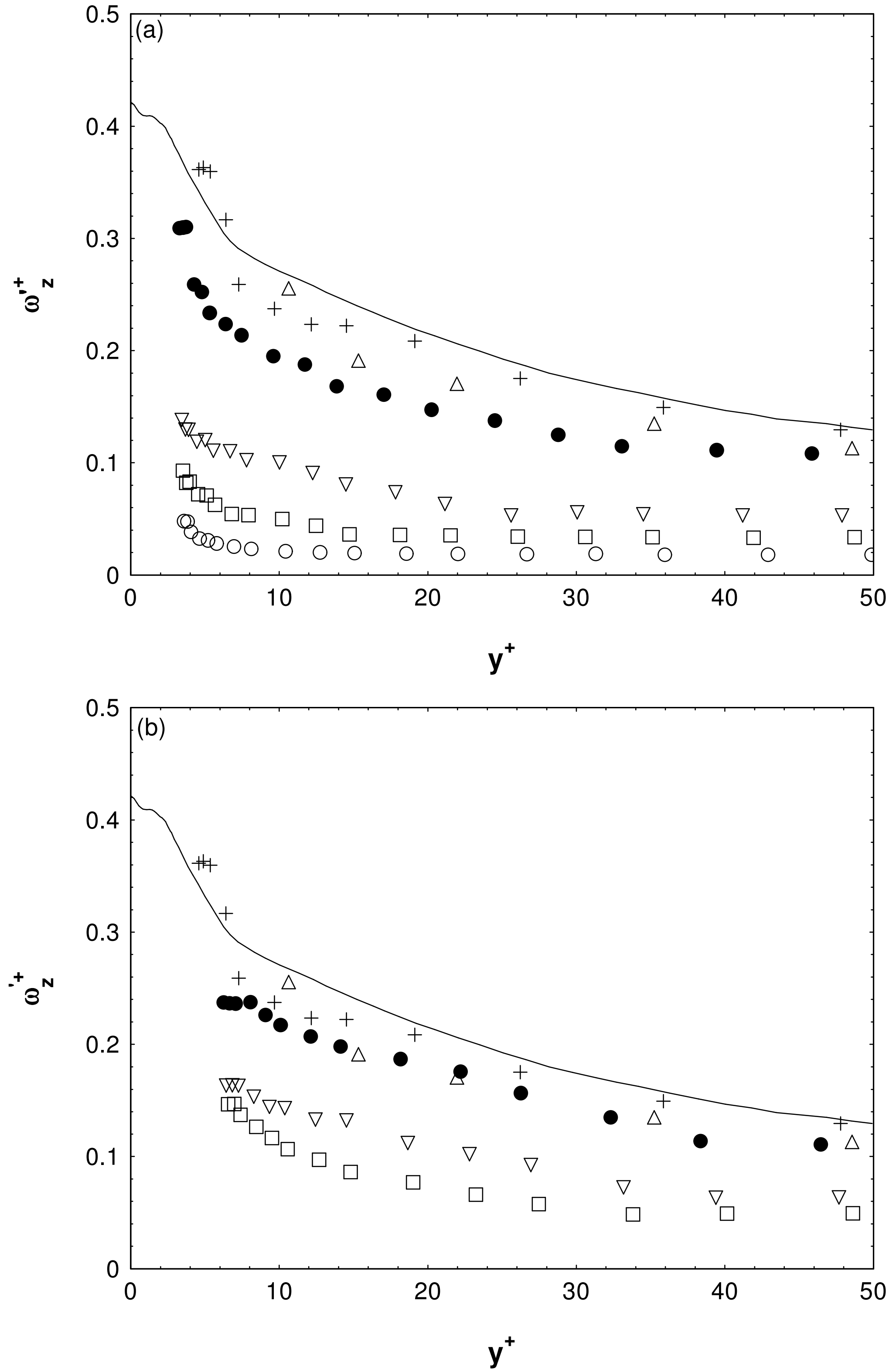

Figure 7: Distributions of the RMS spanwise vorticity in the wall region for (a) $R_{\theta o}$ = 670; (b) $R_{\theta o}$ = 1400 and at x / δ_o = 3. λ : σ = 0; σ : σ = 1.7; ♦ : σ = 3.3; ϒ : σ = 5.5; —: Spalart (R_θ = 1400); +: Klewicki & Falco (R_θ = 1010, 1990); ρ : Rajagopalan & Antonia (R_θ = 1450, 1993).

All the measured data are lower than DNS data. The interesting result emerging is the significant reduction in ω_z' when suction is applied. The level of departure from $\sigma = 0$ increases with σ but reduces as $R_{\theta o}$ increases. The reduction can be linked to a stabilisation of the near-wall vortical structures. Djenidi et al.'s flow visualisations (2002) showed that suction have a stabilising effect in the spanwise direction. The effect of this stabilisation is likely to weaken the vorticity, and thus diminish the strength of the vortices in the near-wall region of the boundary layer. This would modify the turbulence level downstream of the strip. This argument is consistent with the reduction in the Reynolds stresses in the near-wall region observed in Oyewola et al.'s study (2003). Moreover, since high internal shear layer which contributes significantly (Antonia et al., 1991) to ω'_z ($\omega_z = \partial v / \partial x - \partial u / \partial y$) existing in the near-wall region plays a prominent role in the dynamics of the layer (Johansson et al., 1987), the reduction in ω'^+_z may suggest an alteration in the dynamics of the layer.

The present data indicate that the magnitude of the response of $\omega_z'^+$ to suction reduces as $R_{\theta o}$ increases. For example, relative to $\sigma = 0$, ω'^+_z is reduced by 70% for $R_{\theta o} = 750$ as compared with 55% reduction observed for $R_{\theta o}$ = 1400 when $\sigma = 3.3$. The above results would suggest that the near-wall vortices becomes more intensified as the Reynolds number increases, which in turn would reduce the effect of suction.

5. Conclusions

The influence of Reynolds number on the suction effect on the turbulent boundary layer has been quantified. The results indicate a change of the near-wall structure as reflected in a significant reduction in the correlation coefficient and structural parameter relative to undisturbed boundary layer. While the reduction of correlation coefficient by suction suggest strong decorrelation between u and v fluctuations, the reduction of structural parameter suggest an alteration in the efficiency of turbulence in generating shear stress. Altogether, the results imply a structural change in the layer. The effect is increased as the suction rate is increased, but its magnitude is reduced when the Reynolds number is increased. The result is supported by the variation of the spanwise vorticity in the near-wall region. Relative to no suction, spanwise vorticity is significantly reduced in the near-wall region when suction was applied, suggesting an alteration in the dynamics of the layer. The magnitude of this alteration is reduced when $R_{\theta o}$ is increased.

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