FREE STREAM TURBULENCE INDUCED DISTURBANCES IN A UNIFORM SUCTION BOUNDARY LAYER

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ABSTRACT

An experimental study on the effect of boundary layer suction on the development of boundary layer disturbances introduced by free stream turbulence has been carried out. In the study an asymptotic suction boundary layer was established in a wind tunnel. Uniform suction was applied over a large area and the boundary layer was nearly constant over a length of 1800 mm. Measurements were made both with and without suction so comparisons between the two cases could easily be made. Measurements of the development of the mean velocity distribution showed good agreement with theory. Free stream turbulence was generated by three different grids giving turbulence intensities at the leading edge of the plate between 1.4 % and 4.0 %. The free stream turbulence induces disturbances into the boundary layer and it was shown that for the suction case the disturbance level inside the boundary layer saturates at a level which is proportional to the free stream turbulence intensity. In all cases transition was not observed when suction was applied although without suction the two highest levels of grid turbulence gave rise to transition. Despite a twofold reduction in the boundary layer thickness in the suction case compared to the no suction case the spanwise scale of the streaky structures is only slightly decreased.

INTRODUCTION

One of the obvious possibilities to achieve Laminar Flow Control (LFC) in boundary layer flows is to use distributed suction at the surface. A special case is when the so called asymptotic suction profile is obtained. This flow condition is obtained at some distance downstream the leading edge of a flat plate when uniform suction is applied over a large area. An interesting feature is that an analytic solution of the uniform suction problem may be derived from the boundary layer equations resulting in an exponential profile (the asymptotic suction profile). The suction has a similar influence on the profile as a favorable pressure gradient and makes the profile in the fully developed asymptotic region much more stable than the Blasius profile.

The asymptotic boundary layer flow has been dealt with extensively in text books, see for instance Schlichting (1979), and the theory for the mean flow is straightforward. One can easily show that the boundary layer profile $U(y)$ becomes

$$U/U_\infty = 1 - e^{-yV_0/\nu}$$

where U_∞ and V_0 are the constant free stream velocity and the suction velocity, respectively. The displacement thickness for the boundary layer is

$$\delta_1 = \nu/V_0,$$

whereas the momentum thickness is $\delta_2 = \frac{1}{2}\delta_1$ and the shape factor $H_{12} = 2$. The Reynolds number based on the displacement thickness can then be written as the ratio between the free stream velocity and the suction velocity

$$R = U_\infty/V_0.$$

To obtain the stability characteristics of the suction boundary layer the normal velocity component of the mean flow, i.e. the suction velocity at the wall, can be incorporated in the disturbance equation and this gives a slightly modified Orr-Sommerfeld equation. Also the boundary condition of the normal fluctuation velocity, due to pressure fluctuations above a porous plate, need to be considered. This give rise to an additional equation that has to be satisfied at the wall, but which reduces to the standard boundary condition in the limit when the permeability approaches zero, see Gustavsson (2000). Drazin & Reid (1981) cites results showing that the critical Reynolds number for two-dimensional waves increases with two orders of magnitude as compared to the Blasius boundary layer.

Experimental work on the suction boundary layer has to some extent be done earlier, but mainly devoted to determination of the mean flow (se Schlichting (1979) and references therein). The present work deals with the effect of suction on the development of disturbances induced into the boundary layer by free stream turbulence. It is well known that for the Blasius boundary layer free stream turbulence induces disturbances into the boundary layer which give rise to streamwise oriented structures of low and high speed fluid (see e.g. Matsubara & Alfredsson (2001)). These structures grow in amplitude and establish a spanwise size which is of the order of the boundary layer thickness far away from the leading edge. When the streaks reach a certain amplitude they break down to turbulence, probably through a secondary instability mechanism (see for instance Andersson et al. (2001) and references therein). The present study shows the development of such structures in the asymptotic suction boundary layer and it is shown that in this case the growth of the streaks is limited and that this also hinders breakdown to turbulence.

BOUNDARY LAYER DEVELOPMENT

If an impermeable area is considered from the leading edge to where the suction starts the boundary layer will grow and a Blasius velocity profile develops until the boundary layer encounters the porous plate. There the profile will start to undergo a transformation from the Blasius state to the asymptotic suction state. This spatial evolution can from a simple approach be described through a non-dimensional evolution equation. The first step is to introduce an indirect x- and y-dependent stream function according to

$$\psi = \sqrt{\nu x U_\infty} f(\xi, \eta)$$

$$\text{and} \quad \xi = x\frac{V_0}{U_\infty}\sqrt{\frac{U_\infty}{\nu x}}; \qquad \eta = y\sqrt{\frac{U_\infty}{\nu x}};$$

where the streamwise- and normal velocity components are recovered through

$$u(\eta) = U_\infty \frac{\partial f}{\partial \eta} \qquad \text{and}$$

$$v(\eta) = \sqrt{\frac{U_\infty \nu}{4x}} \left(\eta \frac{\partial f}{\partial \eta} - \xi \frac{\partial f}{\partial \xi} - f \right).$$

When applied to the boundary layer equations we get the following third order non-linear partial differential equation

$$\frac{\partial^3 f}{\partial \eta^3} + \frac{1}{2} f \frac{\partial^2 f}{\partial \eta^2} + \frac{1}{2} \xi \left(\frac{\partial f}{\partial \xi}\frac{\partial^2 f}{\partial \eta^2} - \frac{\partial f}{\partial \eta}\frac{\partial^2 f}{\partial \eta \partial \xi} \right) = 0,$$

with the corresponding boundary conditions

$$\left. \begin{array}{lll} f & = & \xi \ \text{(suction)} \\ \frac{\partial f}{\partial \eta} & = & 0 \ \text{(no-slip)} \end{array} \right\} \quad \text{at} \quad \eta = 0$$

$$\text{and} \quad \frac{\partial f}{\partial \eta} \to 1 \quad \text{as} \quad \eta \to \infty.$$

The first solution obtained from such evolution equation with an impermeable entry length was obtained by Rheinboldt (1956) through series expansion. The ansatz of a stream function and dimensionless variables for deriving the evolution equation are not to be confused with similarity solutions. The stream function is dependent on two variables and becomes 'similar' when the asymptotic suction state is reached.

Results obtained from the above equations, such as the needed length for reaching the asymptotic state for different suction velocities (V_0) and free stream velocities (U_∞), was used when designing the present experiment.

EXPERIMENTAL SET-UP

An experimental set-up has been developed to establish the asymptotic suction profile boundary layer in the MTL-wind tunnel at KTH. Extensive hot-wire measurements have been carried out in order to investigate the influence how this boundary layer flow is affected by free stream turbulence.

A schematic of the experimental set-up is shown in figure 1. The test section is 7 m long, 0.8 m high and 1.2 m wide. The MTL-wind tunnel has a 5 degree of freedom traversing mechanism, which is convenient for boundary layer traverses as well as X-probe calibration.

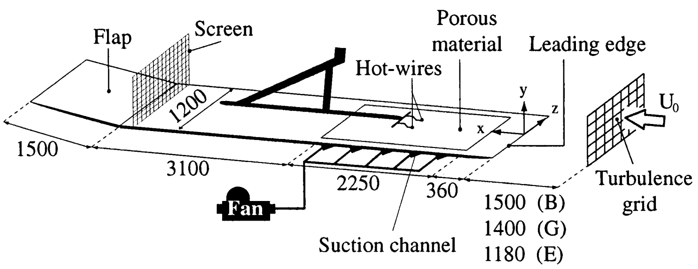

Figure 1: Experimental set-up. The three turbulence generating grids give different turbulence intensities at the leading edge. $Tu_B = 1.4\%$, $Tu_E = 4.0\%$ and grid G being an active grid was used at $Tu_G = 2.2\%$.

An asymmetric leading edge was specially designed for this experiment which results in a short pressure gradient region at the leading edge. A fine-meshed screen was installed at the end of the test section just upstream the trailing edge flap (going into the diffuser). The screen was needed to compensate for the extra blockage below the plate due to suction channels and tubing.

Free stream turbulence was generated by three different grids (two passive, B and E, and one active, G) mounted at different distances from the leading edge. The grids gave turbulence intensities ($Tu = u_{rms}/U_\infty$) at the leading edge of the plate of 1.4%, 4.0% and 2.2%, respectively.

The test plate is built as a sandwich-construction. It is constructed from a base plate of aluminium with a frame, and is designed having a 2250 mm long plenum chamber starting 360 mm from the leading edge. Inside the plenum chamber distance elements made of T-profiles are glued in order to support the porous plates and avoid bending the plates when suction is applied. On these T-profiles three porous plates with the total dimension $3.2 \times 2250 \times 1000$ mm^3 (thickness, length, width) were mounted into the frame plate. The porous plates consist of a sintered plastic material with an average pore size of 16 μm and the surface can be considered smooth. On a spanwise line in the base plate five large holes (30 mm) were drilled at nine positions to where nine suction channels where connected. This was sufficient to achieve uniform pressure in the plenum chamber.

The porous material was characterized through a piston-experiment where the permeability of the porous material was determined. This was done by placing a piece of the porous material (thickness $d = 3.2$ mm) at the end of a 0.9 meter, 4 cm diameter Plexiglass pipe and measuring the pressure drop over the porous material when a piston was forced through the pipe with a linear motor. This was done at various velocities (V) in the range 0.4-1.2 cm/s and it was found that the pressure drop Δp varied in linear proportion to the flow velocity through the material. From this the permeability (k) of the material was determined from Darcy's law as $k = Vd\mu/\Delta p$ where μ is the dynamic viscosity. From these measurements it was found to be $k = 3.7 \times 10^{-12}\text{m}^{-2}$.

In the present experiments the wind tunnel ceiling was adjusted so that the pressure gradient along the test section was close to zero for the no suction (Blasius flow) case. When suction was applied less than 1 % of the flow in the test section was removed. This gives rise to a slight adverse pressure gradient, however the effect on the mean boundary layer flow is very small as compared to the suction itself.

Single hot-wire probes operating in CTA mode were used to measure the streamwise velocity components. One probe could be traversed in all three spatial directions whereas a second probe was located at a specific spanwise position (in the centre of the tunnel). Both probes were traversed in the x and y-directions by the same traversing system and their x and y positions were the same. This made it possible to make two-point spanwise space correlation measurements. The results presented in this paper are from single wires only, but X-probe and LDV measurements have also been performed and will be reported at a later stage.

The single probes were made of 2.5 μm platinum wires with a distance between the prongs of approximately 0.5 mm. The calibration function according to Johansson and Alfredsson (1982) was used, where an extra term is added to King's law for compensation of natural convection which makes it suitable for low speed experiments.

RESULTS

The experiments reported here were made at a free stream speed of 5 m/s and a suction speed of 1.40 cm/s. This gives an asymptotic boundary layer thickness of 5 mm and

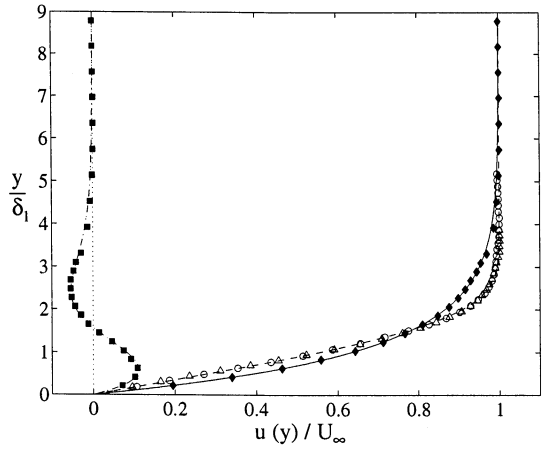

Figure 2: Velocity profiles for the Blasius and the asymptotic suction boundary layers. No suction (unfilled-), suction (filled markers) and theory (lines). Asymptotic suction profile (solid line) (◇) at $x = 1800$, Blasius profiles (dashed line) (○) at x = 300 mm and (△) at x = 1800 mm. (□) is the mean deviation (dash-dotted line).

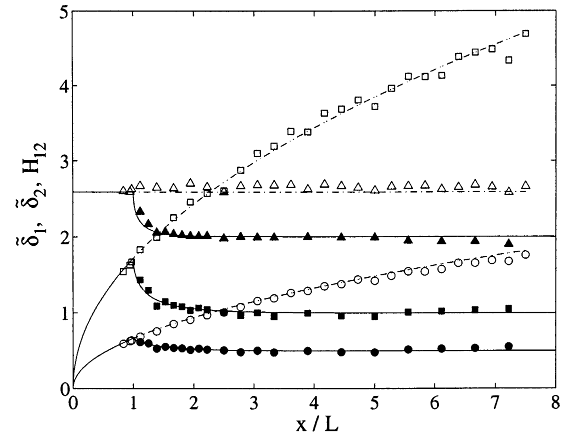

Figure 3: Experimentaland theoretical results of integral boundary layer parameters. No suction (unfilled-) and suction (filled markers). (□) $\tilde{\delta}_1$ and (○) $\tilde{\delta}_2$ are the displacement- and momentum thickness, respectively, normalized with $\frac{1}{L}(\frac{UL}{\nu})^{1/2}$. (△) H_{12} is the shape factor.

a Reynolds number based on the displacement thickness of 360. In figure 2 both experimental data and the theoretical distribution are plotted for the Blasius profile measured at x=300 and x=1800 mm and the asymptotic suction profile measured at x=1800 mm. The agreement between the three experimental profiles and the corresponding theoretical profiles are excellent. Even at x=1800 mm the measured Blasius profile agree well with theory indicating a steady Blasius boundary layer throughout the measurement area when no suction is applied. It is notable that the hot-wire reading very close to the wall is quite accurate, making it possible to measure velocities down to 0.5 m/s without any discrepancy from the theoretical curve. This is due to the calibration function as well as the low heat conductivity of the porous material. Also plotted is the deviation between the suction profile and the Blasius one which clearly reveals the fuller shape of the suction profile.

Also for the development of the boundary layer from the Blasius towards the asymptotic profile shows good agreement with theory, i.e. the evolution equation, and can be observed in figure 3 (note the scaling). The dash-dotted line is the Blasius solution and the solid line originate from the evolution equation.

The suction velocity may be verified simply by measuring a velocity profile in the fully developed asymptotic suction region. The pressure below the porous material was measured at 40 different positions, showing a homogeneous pressure distribution below the plate, making it possible to control the suction velocity accurately. The absolute error of the suction velocity was estimated to ± 0.02 cm/s. By assuming an exponential velocity profile and fitting it to the measured profile, by means of the least square method, the suction velocity was determined to 1.49 cm/s, which should be compared to the 1.40 cm/s kept during the measurements.

An experiment was also made with wave disturbances (TS-waves) generated through a transverse slit in the plate by means of a loudspeaker. The decay rate for 2D waves compared well with linear stability calculations. However, these measurements are not presented in this paper.

Free stream turbulence gives rise to regions of high and low velocity (streaky structures) and in a Blasius boundary layer the streamwise disturbance energy grows in linear proportion to the downstream distance. These streaky structures move slowly in the spanwise direction and if the streamwise disturbance amplitude is measured (u_{rms}) it is seen to increase with the downstream distance when no suction is applied, whereas in the suction case this amplitude increase was found to be eliminated and the u_{rms}-profiles collapse on each other independent of the downstream position. This can be observed in figure 4 where the u_{rms}-profiles are plotted for both cases, i.e. with and without suction. The position above the plate, where the maximum u_{rms}-value appears, does hardly change in y/δ_1-units and is approximately 1.5, this corresponds to 1/2- and 1/3 of the boundary layer thickness without suction and with suction, respectively. The results are similar for the other grids as well.

In figure 5 the disturbance amplitude, for

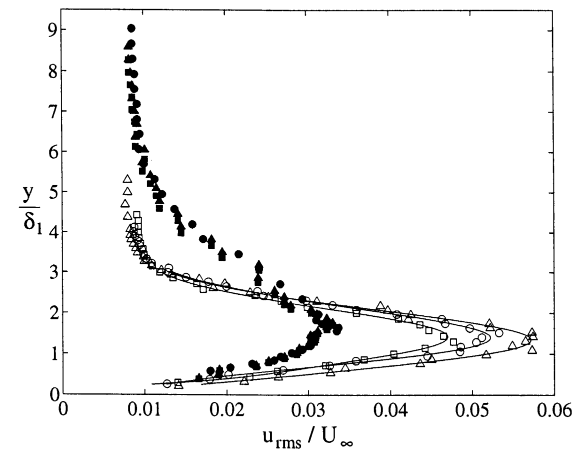

Figure 4: u_{rms}-profiles for different downstream positions from the leading edge with Tu_B. No suction (unfilled-) and suction (filled markers). (□) x = 800 mm; (○) x = 1000 mm and (△) x = 1200 mm. Solid lines are curve fits to data.

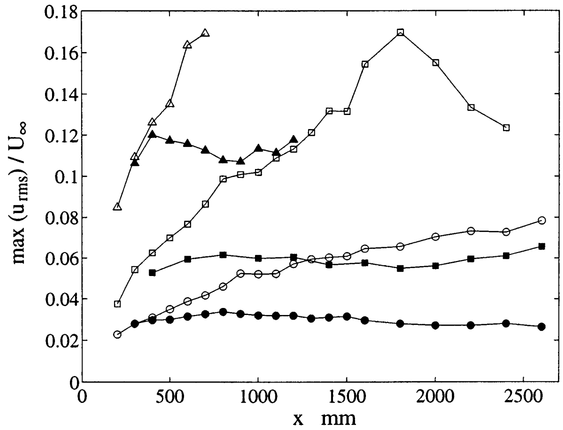

Figure 5: Disturbance amplitude vs downstream distance from the leading edge. No suction (unfilled-) and suction (filled markers). (○) Tu_B; (□) Tu_G and (△) Tu_E.

different free stream turbulence intensities, is plotted versus the downstream distance from the leading edge. For the no suction cases the disturbance amplitude has been found to grow in proportion to the $x^{1/2}$ and a similar development is observed here. For grid B transition do not occur over the length of the measured region, despite the fact the the u_{rms}-level is above 6% at the end. For grid G a maximum of nearly 17 % in the turbulence intensity is found at x ≈1800 mm. Such a maximum is usually observed in the intermittent region where the flow consists both of laminar regions and turbulent spots. Further downstream the intensity decreases which is what is expected when the flow goes towards a fully developed turbulent stage. For grid E, measurements were only made until x =700 mm where a similar high level was observed. For all suction cases, however, it is found that transition do not occur. Instead the fluctuation level inside the boundary layer reaches an almost constant level which is close to that existing where the suction starts. An interesting observation is that this level is proportional to the level of the free stream turbulence.

Two-point correlations of the streamwise velocity component show that the spanwise scale of the streaky structures is only slightly decreased by suction, despite a twofold reduction in boundary layer thickness, indicating the importance of the scale of the free stream turbulence. In figure 6 two 2D space correlation plots are shown, 6a) when no suction is applied and 6b) when suction is applied. The x-position is 1800 mm, i.e. in the fully developed region for the suction case. It is well known that the separation distance where the correlation coefficient (R_{uu}) shows a distinct minimum can be interpreted as half the dominating spanwise wave length of the streaks. In figure 6 this minimum is clearly distinguishable for both cases.

Matsubara and Alfredsson (2001) showed that the spanwise scale of the streaks observed further downstream from the leading edge seems to depend on the free stream turbulence scales introduced into the boundary layer at an early stage of the receptivity process. Thereafter this scale seems to adapt to the boundary layer thickness and grows in proportion to this thickness. In the suction case the scenario is slightly different since the spanwise scale is hardly changed compared to the spanwise scale observed in the Blasius boundary layer, and this despite the fact that the boundary layer thickness is only half of that in a Blasius layer. This result was obtained for all three free stream turbulence intensities tested. The conclusion from figure 6 is that the effect of suction on the streaks is compression, i.e. the boundary layer is compressed in the wall-normal direction reducing the boundary layer thickness but preserving the spanwise scale creating an wider structure in terms of boundary layer thickness as compared to the Blasius case. This indicates the importance of the scale of the free stream turbulence, on the disturbance structure inside the boundary layer.

In figure 7 the evolution of the spanwise scales of the streaks from all three grids are shown. The minimum value of the correlation coefficient (R_{uu}) were determined by fitting a third order polynomial to the measured data and the zero passage of R_{uu} by fitting a second order polynomial. In figure 7a) we see the largest increase of the spanwise scale compared

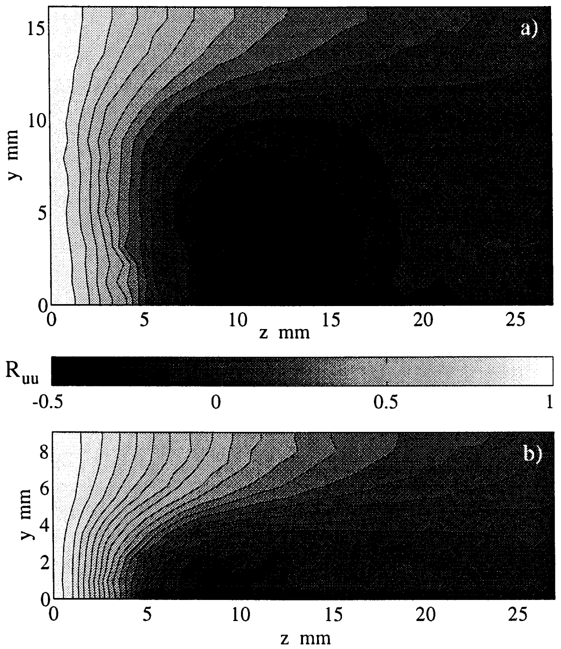

Figure 6: Two-point correlation measurements of the streamwise velocity component with Tu_B. yz-plane at $x = 1800$ mm consisting of 504 measuring points in a) No suction applied, and 392 in b) Suction applied.

to the other free stream turbulence intensities in b) and c). If a discrepancy between the no suction- and suction case should be pointed out a tendency towards slower growing spanwise scale in the suction case compared to the no suction case may be observed. Worth mentioning is that the spanwise scale of the streaks seem to decrease with increasing free stream turbulence intensities according to figure 7. As can be seen in figure 7d) the zero passage is an equally good measure of the spanwise scale as the minimum value of the correlation coefficient. The zero passage may be hard to interpret physically but is easier to determine from an experimentalist's point of view. All ratios of the minimum value of the correlation coefficient and the zero passage of the present data collapse at a value of 1.68 ± 0.23.

SUMMARY

A successful experimental set-up to study the stability and disturbance structure of the asymptotic suction boundary layer has been developed, and excellent agreement with mean flow theory has been obtained. In the boundary layer with free stream turbulence disturbance growth have been shown to reach a saturation level, which is proportional to Tu. We also find that transition is inhibited for all cases with suction. The spanwise scale of the streaks is maintained, when suction is applied compared with the no suction case, and this despite a twofold boundary layer thickness reduction. The saturation of the disturbance amplitude in the boundary layer indicates that the growth is inhibited and maybe that the dynamics of the streaks become different in the suction case. Further theoretical studies of non-modal growth of streaky structures in the asymptotic boundary layer may give further information on the interpretation of the present results.

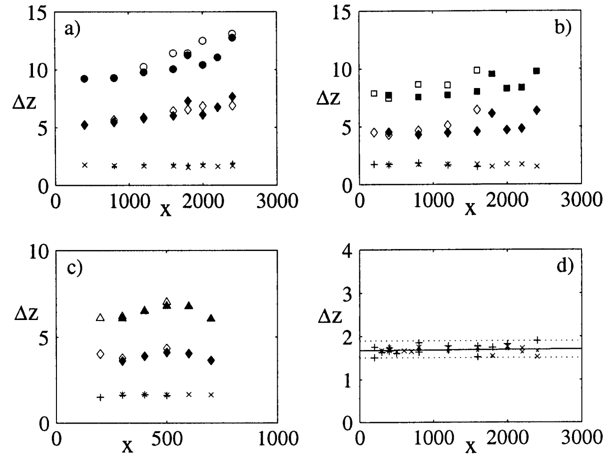

Figure 7: Evolution of the spanwise scale of the streaks. No suction (unfilled-) and suction (filled markers). a) (○) min(R_{uu}) and (◇) zero(R_{uu}) for Tu_B. b) (□) min(R_{uu}) and (◇) zero(R_{uu}) for Tu_G. c) (△) min(R_{uu}) and (◇) zero(R_{uu}) for Tu_E. d) min(R_{uu})/zero(R_{uu}) for all grids. (+) no suction and (×) suction.

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