

THE EFFECT OF A SQUARE GROOVE ON A BOUNDARY LAYER

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ABSTRACT

Laminar and turbulent boundary layer flows over a single square wall groove have been investigated in a water tunnel facility using the LDV technique. Accurate near-wall velocity profiles have been measured. For the laminar case, a sharp rise in c_f/c_{f_0} is observed both immediately before and after the groove. It then relaxes downstream to unity when compared to Blasius. The laminar result compares well with a finite element method numerical simulation. The turbulent case also exhibits a rise in c_f/c_{f_0} immediately before and after the groove. Downstream of the groove, c_f/c_{f_0} undershoots before relaxing back to unity (compared to the equivalent smooth wall case). The impulsive change in the no-slip boundary condition affects the production of the near-wall events responsible for turbulent mixing. This results in a temporary decrease of momentum exchange and a corresponding decrease in c_f/c_{f_0} .

INTRODUCTION

Passive and active manipulations of the flow field may result in drag reduction and a corresponding performance enhancement. Research into drag reduction received extra impetus during the fuel crises of the early 1970's. In particular, passive control has been extensively researched. The advantages of drag reduction include increased machine efficiency and/or performance. For example, skin friction drag of transport aircraft can amount to nearly 50% of the total drag (Coustols & Savill, 1988). In this industry, drag reduction is synonymous with increased range, speed, manoeuvrability, greater payloads or decreased fuel consumption. For the majority of internal flows, 100% of drag is due to skin friction. A drag reduction for internal flows will result in improved through-put, reduced pumping power or reduced duct sizes and

costs (Gad-el-Hak, 1989).

In the past, surface roughness has been extensively investigated as a means of modifying the turbulent boundary layer. d-type roughness, a surface modified with transverse square grooves arranged in a pitch to height ratio of 2:1 (Tani, 1987), has also been investigated mainly because of the possibility that a boundary layer can be exactly self-preserving on such surfaces (Rotta, 1962). For an equilibrium flow of this type with an external zero pressure gradient the skin friction is constant. It has been suggested that sparsely spaced square grooves, optimally located, could result in an overall reduction in turbulent skin friction (Tani et al., 1988). The current investigation is concerned with the effect of just one square groove on both laminar and turbulent boundary layers in an effort to study in detail the skin friction variation associated with this disturbance. To achieve this goal, the LDV technique will be used to accurately measure the near-wall velocity gradient.

EXPERIMENTAL SET-UP

Both laminar and turbulent experiments have been conducted in a closed circuit constant-head vertical water tunnel. The tunnel is driven by a 5 kW variable speed centrifugal pump. A float valve, electrically tethered to the electric motor of the pump, ensures that the head remains constant. The desired freestream velocity, and therefore Reynolds number, is obtained with a pneumatically adjusted butterfly valve. The maximum fully developed Reynolds number, based on the momentum thickness, is nominally 1400 in the measurable region of the test section. Turbulence management is achieved by the combination of a very large pre-delivery tank, baffle, wire screen and honeycomb. The flow enters the test section via a 5:1 contraction. Enforced boundary layer transition (when

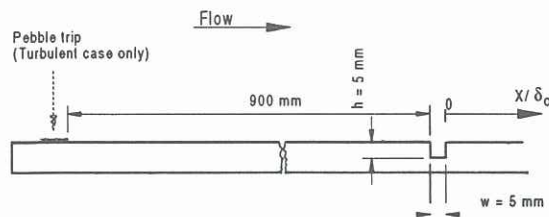


Figure 1: Experimental geometry, wall embedded square groove.

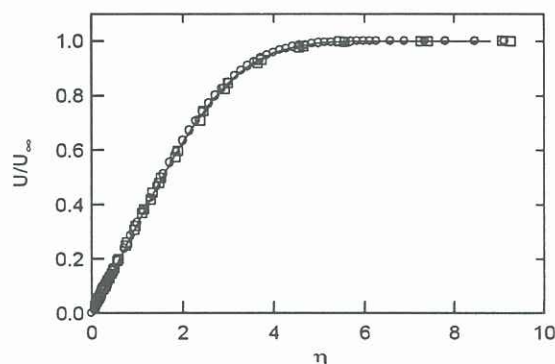


Figure 2: Laminar velocity profile, $Re_\theta = 110$. (O, CFD; □, LDV; —, Blasius).

required) is fixed 100 mm from the contraction exit by a 4.5 mm pebble strip of 50 mm width and test section span. The acrylic working section is 2m long, 260 mm × 260 mm square and has 20 mm thick transparent walls. The free-stream velocity is 45 mm/s for the laminar study and 0.4 m/s for the turbulent study. The transverse square groove is located 0.9 m from the boundary layer trip (it is removed for the laminar investigation) and spans the full width of the working section. It has a height and width of 5 mm. The experimental geometry is shown in Figure 1.

The fibre-optic LDV laser system is powered by a 5W Spectra-Physics Ar-ion laser with a DANTEC color separator and frequency shift system. It was used in forward scatter mode. Only one-component (green, 514.5 nm wavelength) measurements are made. An Enhanced Burst Spectrum Analyzer is used for processing the photomultiplier signal. A 386 PC is used for collection, digitization and data reduction of this signal. An Iridium 100 Silver PearlTM (20 μm average particle size) seeding solution is used to enhance the data collection rate. For the tur-

bulent investigation, measurement points in the outer layer of the profile, typically, have a data rate of 1600 Hz. The data rate for points close to the wall is drastically reduced to as low as 1 Hz. Twenty thousand samples are collected at each point for the majority of the profile but this is reduced to 2000 samples in the inner region. Each profile consists of approximately 50 points.

NUMERICAL METHOD

The general purpose Navier-Stokes solver, *FI-DAP* (FDI, 1993), has been used in a laminar numerical study. The code employs a weak-Galerkin form of the finite element method. A penalty function perturbation de-couples the velocity-pressure coupling. The penalty parameter, ε , is 10^{-9} . Quadrilateral-9 elements (bi-quadratic velocity, discontinuous bi-linear pressure) discretise the flow domain. A steady-state solution is obtained via a fixed-point iterative technique (successive substitution).

The graded Cartesian grid of 1800 Quad-9 elements (≈ 6500 nodes) includes 30×30 nodes within the groove with expansion and contraction ratios of 1.1 from side-to-side and top-to-bottom. The boundary layer is captured with a minimum of 30 nodes graded away from the wall. The freestream boundary is located at a height of $10\delta_0$ above the flat plate. Forty graded nodes model the upstream development length ($10\delta_0$) and 60 graded nodes model the downstream relaxation length ($20\delta_0$). The groove width (w/δ_0) is 0.33. The inlet boundary condition is the experimental profile measured 100mm upstream from the groove. For the freestream and outlet boundary conditions the zero normal stresses, $\sigma_{ij} = -p\delta_{ij} + \mu(u_{i,j} + u_{j,i})$ are set to zero. Nine iterations were required for a converged solution (0.01% error with respect to the previous velocity residual). Approximately 1000s and 36 Mbytes of RAM were needed on a SUN Sparc2 workstation.

LAMINAR RESULTS

For the laminar flow case both a numerical and experimental investigation have been completed. The momentum thickness Reynolds number, Re_θ , is 110 at a distance of 100 mm upstream from the groove. The experimental velocity profile is compared with Blasius in Figure 2. Also included is the CFD velocity profile at the outlet of the computational domain. The

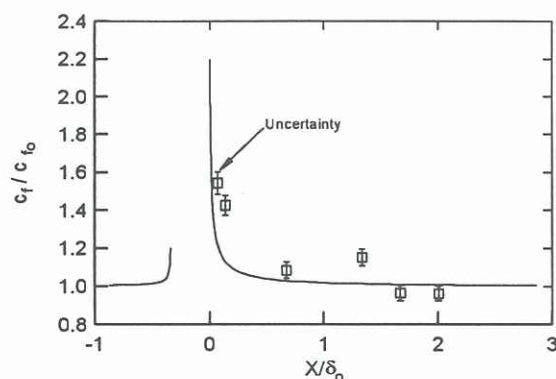


Figure 3: Streamwise development of skin friction. Laminar boundary layer, $Re_\theta = 110$ (—, CFD; \square , LDV).

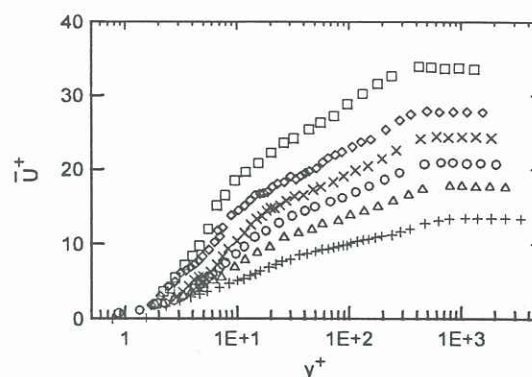


Figure 5: Turbulent mean velocity profiles (LDV. \circ , $X/\delta_0 = -2.0$; $+$, $X/\delta_0 = 0.036$; \triangle , $X/\delta_0 = 0.292$; \square , $X/\delta_0 = 0.91$; \diamond , $X/\delta_0 = 1.09$; \times , $X/\delta_0 = 6.92$).

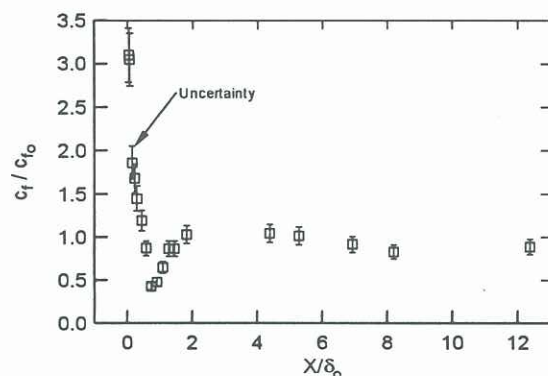


Figure 4: Streamwise development of skin friction. Turbulent boundary layer, $Re_\theta = 1320$ (\square , LDV).

relative errors in the momentum thickness (θ) relative to Blasius for both the CFD simulation (+0.4%) and experiment (-1.6%) are small.

The local skin friction coefficient, c_f is compared to the theoretical (Blasius) boundary layer solution (c_{f_0}) in Figure 3. δ_0 is the reference boundary layer height measured 100 mm upstream from the groove. In the experiment, c_f is estimated from accurate measurements of $\partial U/\partial y$ close to the wall. In the regions immediately before and after the square groove an increase in c_f is observed. This increase in c_f is attributed to local, but intense, negative (favourable) pressure gradients which emanate from the stagnation regions at the leading and trailing edges of the groove. As the flow develops downstream, c_f relaxes back to Blasius and there is no undershoot in c_f/c_{f_0} . The lead-

ing edge and trailing edge c_f/c_{f_0} maxima are 1.2 and 2.2, respectively. The upstream disturbance length is $1.8\delta_0$ and the downstream relaxation length is $4.5\delta_0$. Empirically, the ratio of these maxima appear to approximately equal the recovery/disturbance length ratio.

TURBULENT RESULTS

When the boundary layer is turbulent, the recirculating flow within the groove is unsteady. Flow visualizations (Elavarasan et al., 1995) show that the fluid within the groove alternately experiences inflows and ejections of varying strengths. The Reynolds number, Re_θ , at 50 mm upstream of the groove is 1320. The square groove width (w/δ_0) is 0.17. In the near-wall region the LDV is able to measure \bar{U} in steps of 0.025 mm. Approximately 5 data points were available to resolve the near-wall linear region to give a good estimate of $\partial \bar{U}/\partial y|_0$. The error in the location of the origin was estimated to be no worse than ± 0.5 wall units. The resulting c_f is compared with the corresponding undisturbed turbulent smooth wall case, c_{f_0} , in Figure 4. A sharp rise in c_f has been measured immediately upstream and downstream of the groove. The overshoots in c_f/c_{f_0} are attributed to the local intense negative pressure gradients that emanate from the stagnation regions. From the sharp overshoot at the downstream edge of the groove, a reduction in c_f/c_{f_0} is observed over a distance of about $2\delta_0$. The region of reduction includes an undershoot and oscillatory relaxation back to unity. These observations con-

flict with the results of Choi et al. (1989) and Choi & Fujisawa (1993) who do not observe the undershoot in c_f . It is most probably due to their use of the Clauser chart method for estimating c_f . For this type of flow, the inner region is recovering from the wall perturbation and the assumption of equilibrium, especially in the near-wall region, is questionable. Figure 5 shows the mean velocity profile development. The profiles have been non-dimensionalised by the local values of the wall variables u_τ (friction velocity) and ν/u_τ (length). The effect of the groove is noticeable with a downward shift of the mean velocity profiles that experience a c_f/c_{f_0} overshoot (for example, $x/\delta_0 = 0.036$) and an upward shift for a c_f/c_{f_0} undershoot (for example, $x/\delta_0 = 0.91$). Also observed is the downstream relaxation of the mean velocity profile, which cannot be assumed complete by the last measurement station ($x/\delta_0 = 12.4$).

There is a difference in trend between the laminar and turbulent c_f/c_{f_0} distributions for $x > 0$. At this stage we can only speculate as to the cause of the undershoot in c_f/c_{f_0} downstream of the groove. Momentum exchanges ensure a fuller and almost uniform turbulent mean velocity profile with increased c_f compared to a laminar profile. To reduce skin friction drag in a turbulent boundary layer, modification of the processes that lead to momentum exchange is required. Quasi-streamwise vortices are assumed responsible for the near-wall activities that cause momentum exchange. The effect of the groove is to impulsively perturb the no-slip boundary condition. This temporarily suspends the production of new quasi-streamwise vortices and reduces the near-wall activities which lead to momentum exchange. The result is a reduction in the c_f/c_{f_0} distribution.

CONCLUSIONS

The effect of a small square groove on laminar and turbulent boundary layers has been investigated. An LDV system has been used to accurately measure the near-wall velocity gradient. In both cases, there is a sharp rise in c_f/c_{f_0} immediately before and after the groove due to a local intense favourable pressure gradient. The laminar flow then relaxes to Blasius with downstream distance. The ratio of the upstream disturbance length to downstream relaxation length is approximately equal to the ratio of c_f/c_{f_0} maxima at the leading and trailing

edges. The turbulent c_f/c_{f_0} distribution falls below unity downstream of the groove. This undershoot has been attributed to the near-wall turbulent flow response to an impulsive change in the no-slip boundary condition. The wall perturbation interferes with the production of new quasi-streamwise vortices. This, in turn, modifies the near-wall activities responsible for momentum exchange and turbulent skin friction.

ACKNOWLEDGEMENT

The support of the Australian Research Council is gratefully acknowledged.

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