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Turbulent Boundary Layer Development Along a Streamwise Edge (Chine) - Mean Flow.

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ABSTRACT

Many water and air transport vehicle designs have a hard chine in their geometry. The drag on such designs depend on the boundary layer development over the chine. As an initial approximation we idealize the chine as a streamwise edge with a 90 degree corner and investigate the flow on the outside of the corner. The geometry is simple but the flow development is complex and three dimensional with secondary flows. In this paper we report integral properties of the boundary layer development derived from pitot tube mean flow measurements.

INTRODUCTION

A number of investigations have been completed at the University of Melbourne to clarify the effects of extra-strain rates on the development of turbulent boundary layers (see the review by Saddoughi - also see Saddoughi & Joubert and Panchapakesan et.al). These studies document the effects of extra-strain rates in progressively more complex flows to facilitate understanding of the flows around real transport vehicles. In this paper we describe the flow on the outside of an edge with a 90 degree corner aligned with the flow direction.

Davies & Young and Elder investigated the flow past a plate of finite width with streamwise edges. Townsend discusses their work briefly in his book (Section 7.19). The flow development along the inside of a 90 degree corner has been studied in detail both as part of a duct flow and as an unconfined corner flow. If the duct flow is fully developed then the streamwise gradients of turbulence quantities along the axial direction should be zero. Streamwise gradients are not zero in the unconfined corner flow. Flow along a streamwise corner has been studied by Bragg and Mojola & Young. Flow along a streamwise corner in a duct has been studied by many investigators (see for example, Brundrett & Baines and Perkins).

These three classes of flows - finite width plate, unconfined internal corner and the corner in a duct - are all characterized by the generation of stress induced secondary flows. The secondary flows are generated by the production of mean streamwise vorticity (see Bradshaw). The mechanism that dominates the production of mean streamwise vorticity can be identified with particular terms in the equation for the mean streamwise vorticity. This can be either the products of mean velocity gradients (the 'skewing' terms) or differences in the second derivatives of Reynolds stresses. These two kinds of secondary flows - skew induced and stress induced - are also referred to as Prandtl's first and second kinds in earlier literature. These secondary flows give rise to three dimensional mean velocity fields which significantly influence the development of the turbulent flow field.

Elder's study serves as the starting point for our investigation. He made a detatiled study of the mean velocity fields and wall shear stresses of the edge regions of thin flat plates and low-aspect ratio bars. From these measurements he deduced the nature of the secondary flow. We report here mean velocity measurements in the axial direction over the chine. Secondary flow measurements and the turbulence field characterization are deferred to a subsequent paper.

EXPERIMENTAL METHOD

The experiments were carried out in a large closed circuit wind tunnel at the University of Melbourne. The test section of this tunnel has an octagonal cross-section derived from a rectangle of size 1.3 m by 1.68 m. The test section is 6.5 m long. A schematic diagram of the test section is shown in figure 1. A horizontal and a vertical surface of half the tunnel width and covering the entire length of the tunnel test section intersect at the center of the tunnel to make up the chine. The surfaces are made of varnished fiber (MDF) boards of 18 mm thickness. Air flows around both sides of the chine surfaces with only a nominal blockage by the support structure. The test section has slotted walls to minimize the effects of blockage.

The leading edges of the chine surfaces were constructed with lengths of an aluminium airfoil which blend with the tapered MDF boards to avoid separation (see figure 2.). The airfoil is symmetric and is

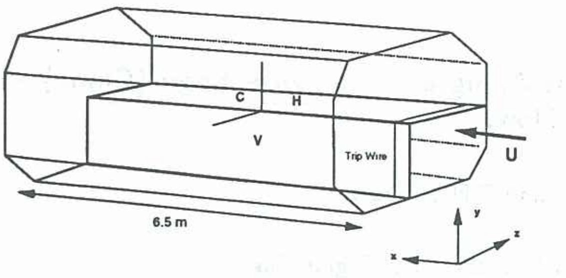

Figure 1: Schematic diagram of the test section with the chine.

aligned with the direction of the mean flow. The flow is tripped with a straight wire (stainless steel tube of 1.2 mm dia.) about 8 cm from where the chine board merges with the airfoil. The location of the trip wire is taken as the reference for axial distance measurements and the chine edge as the reference for lateral distances. The leading edge airfoils were also milled at 45 degree angles and joined. A section of the airfoil from points S to L indicated by a dotted line in the figure lies above the plane formed by the chine board. This implies that a small portion of the airfoil corner region lies in the corner region formed by the extensions of the planes of the chine boards.

The unit Reynolds Number of the flow studied is 6.8×10^5 corresponding to a nominal free stream velocity of 10 m/s. A pitot tube of the 'boundary layer type' was used to measure the mean flow velocities. The diameter of the total pressure tube was 0.7 mm. The pitot tube was mounted at the end of a long sting of a small airfoil section and inserted through narrow slits in the roof of the tunnel or the side wall of the tunnel. The sting arm was mounted on an X-Y traverse.

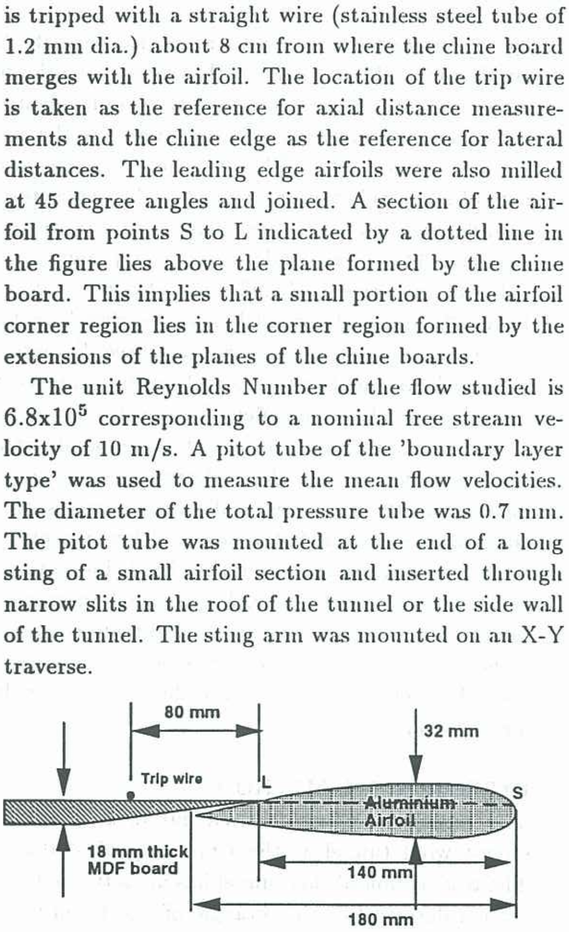

Figure 2: Detatils of leading edge construction.

The probe was traversed at different lateral locations on the horizontal and vertical chine surfaces indicated by H and V in the schematic diagram shown in figure 3. In mean velocity traverses in the region H and V the probe was pressed to the surface and withdrawn in small increments. The probe lift-off from the surface was identified by the change in slope. The first data point was used as input to calculation of the friction velocity by the Preston tube method. In the corner region, indicated by C, the probe was traversed along seven lines of constant angles with an interval of

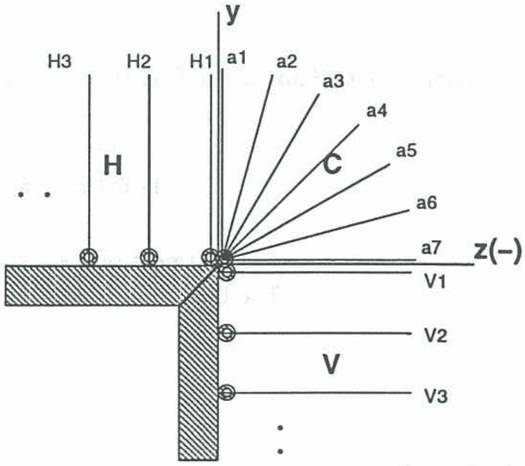

Figure 3: Probe traverse lines.

15 degrees. The starting position for all the angular traverses was the same as shown in the figure. The angular traverses were made by using both X and Y stepper motors.

RESULTS

We plot the boundary layer thicknesses in figure 4. The values far from the chine corner are termed the 2-D values. We compare the present results with those of Erm (1988) and Marusic (1991). Both these measurements were at the same nominal free stream

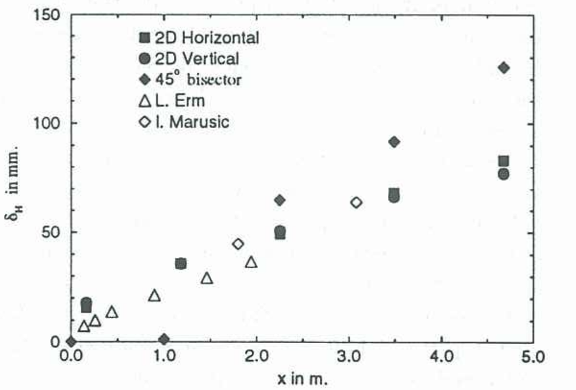

Figure 4: Axial variation of boundary layer thicknesses.

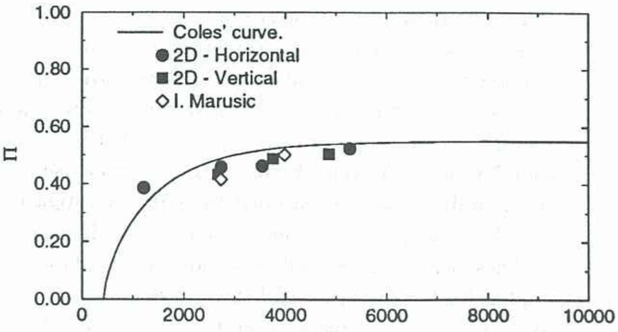

Figure 5: Coles parameter Π versus R_θ.

speed and used the same tripping device (1.2 mm wire) but have slightly different flow histories to the trip wire. The results indicate that the present flow is slightly thicker initially than Erm's measurements but seem to agree with it asymptotically. Marusic's

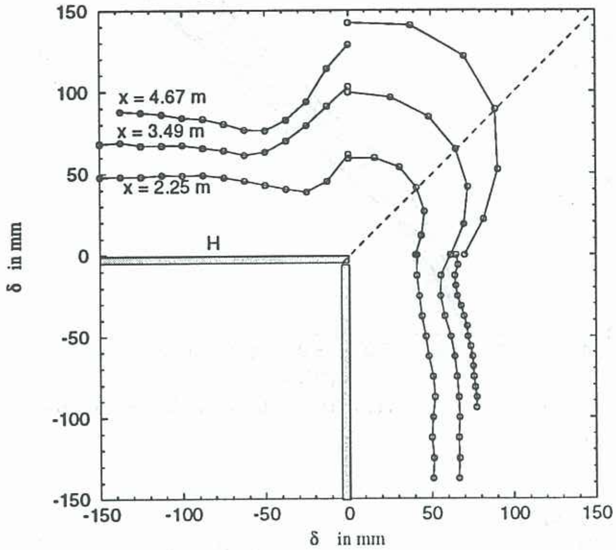

Figure 6: Lateral variation of boundary layer thickness.

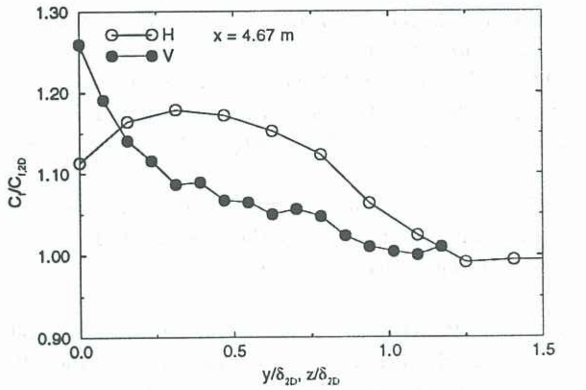

Figure 7: Lateral variation of skin friction coefficient.

measurements made farther downstream agree better. Coles' wake parameter variation with R_θ also agrees with other measurements as shown in figure 5. These comparisons indicate that the boundary layer away from the corner develops as a standard 2-Dimensional flat plate boundary layer. The thickness of the boundary layer along the 45 degree bisector seems to grow almost linearly for the range shown. This is about 25 to 50 % larger compared to the 2-D values.

The lateral variation of the boundary layer thickness is shown in figure 6. The distances plotted in the corner region are along the corresponding angles. The general shape of the variation is similar to a composition of Elder's measurements over a single plate. Elder's contour profiles for flow over a rod of aspect ratio of 1:2 do indicate a similar thickening over the corner region. Based on this similarity we expect that

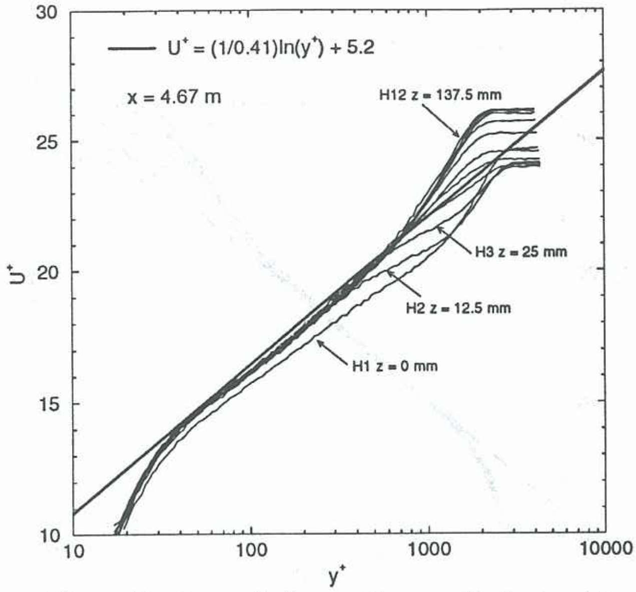

Figure 8: Mean velocity profiles over the horizontal surface.

the secondary flow for the present case consists of two rotating cells similar to the case of the internal corner but with flow directed away from the corner along the bisector and flowing towards the wall beyond the 'dip' region. The core of the cells should be located close to where the thickness is a minimum. This picture needs to be confirmed by measurements of secondary flow velocities.

The flow is not symmetric about the bisector. There is no visible asymmetry in the geometry of the chine save for the different spanwise widths due to the rectangular shape of the test section. Investigators studying the flow over a finite flat plate and internal streamwise corners have indicated that it is difficult to set up a symmetric flow (see Davies & Young, Bragg) and have alluded to small differences in the upstream conditions causing considerable asymmetry of the flow. Detailed measurements in the region x = 0 to 2 m is currently under way to clarify this issue.

The lateral variation of the local skin friction coefficient at the axial location of x = 4.67 m is shown in figure 7. The shape and magnitudes are similar to what Elder presents for flow over small aspect ratio bars. The extent of the influence of the corner region is seen to be about one 2-D boundary layer thickness. Applicability of Preston tube method is suspect at the first (H1 and V1) location but beyond that the measurements are reliable and clearly show the difference in the effect of the secondary flow on each surface.

The mean velocity field at x = 4.67 m in the three regions H, V and C are presented in figures 8, 9 and 10. The profiles for H and V regions are presented in wall co-ordinates. The agreement with the log law is very good for all lateral locations except at the first location (H1 and V1). The wake region is significantly

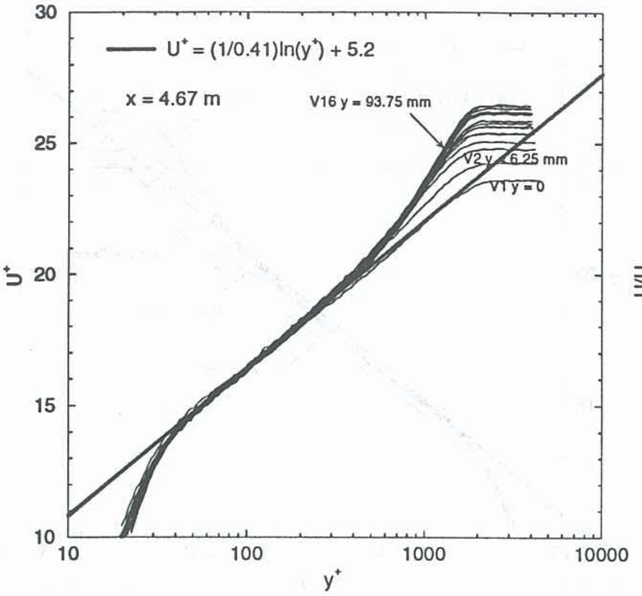

Figure 9: Mean velocity profiles over the vertical surface.

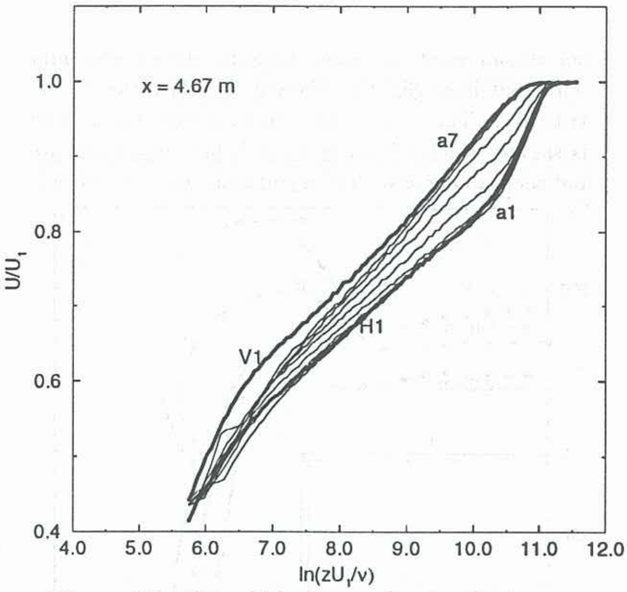

Figure 10: Mean Velocity profiles in the corner region.

influenced by the turbulence field of the corner region. Figure 10 shows the measurements in the corner region. Here normalization with a wall shear stress is not possible for it changes rapidly depending on the local radius of curvature (This was typically 0.5 to 1.0 mm for the chine corner.) The points very close to the corner were also subject to positioning errors. The profiles have been plotted in Clauser variables with the free stream velocity U_1 as the velocity scale. The profiles from locations H1 and V1 are also shown. It can be clearly seen that the velocity profile continuously changes with angle from one to the other.

CONCLUSION

We have presented preliminary measurements of the axial mean flow field for external flow over a streamwise edge. These are consistent with Elder's measurements in the edge region of a thin flat plate and rectangular section bars. The nature of the secondary flow can be inferred to be similar to that found in these flows. There is some asymmetry with respect to the bisector in the corner region. The origin of this asymmetry is being investigated.

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