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AN EXPERIMENTAL STUDY OF A TURBULENT BOUNDARY LAYER IN THE TRAILING EDGE REGION OF A CIRCULATION-CONTROL AIRFOIL

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INTRODUCTION

Researchers and practitioners have known for decades that there is a fundamental change in the forces exerted by a fluid on an object when the motion of that fluid changes from laminar to turbulent. The decomposition into mean and fluctuating parts, and subsequent time-averaging of the Navier-Stokes equations reveals a tensor "stress" quantity, $u_i u_j$, the correlation of velocity fluctuations, as the apparent source of the change.

The improved understanding and prediction of turbulent fluid motion has important consequences in a range of areas, from airplanes to automobiles to artificial hearts. While rapid advances in computer speed and storage offer hope of eventually being able to directly simulate the full, time-dependent Navier-Stokes equations, current practical turbulent flow predictions rely mostly on time-averaged techniques, which require some form of modeling of the turbulent stress tensor.

Successful turbulence modeling seems to be a mixture of empirical knowledge and luck. Clearly the more empirical data a modeler has, the less luck they need. In the past the lack of adequate instrumentation prevented the acquisition of many important data, such as in regions of separation, high 3-dimensionality (i.e., strong spanwise flow), and very close to solid surfaces. The advent of laser Doppler velocimetry (LDV) improved the situation greatly with respect to separated flows, but measuring spanwise velocities and very close to solid surfaces has remained very challenging, if not impossible.

This report describes the development of a new near-wall LDV technique, and its use to measure the full turbulent stress tensor in a highly three-dimensional separated boundary layer flow.

NEAR-WALL LDV

Laser Doppler velocimetry has been in use now for over a quarter of a century. Even a cursory literature survey should provide numerous references on its operation principles and various applications. Given this fact, and its clear superiority over other measurement techniques for complex flows, LDV has not been used nearly as widely as one might have expected. The main reason has been cost; the price for even a single-velocity-component system has often exceeded $50,000 when powerful lasers, high-grade optics, and expensive signal processors were required.

Another deterrent to broader use was the difficulty, even impossibility of application for highly three-dimensional flows (because of the extraordinary optical access required to measure all three velocity components) and flows very close to solid surfaces (because of problems with glare).

Until recently, most LDV systems relied on single-realization burst detectors to process the scattered light signals and translate them into Doppler frequencies, and thus velocities. These "counters" had numerous drawbacks, including: minimal signal quality discrimination, a susceptibility to noise-induced error, large numbers of "fringe crossings" required, and the ability to process only a single component of velocity (thus requiring additional counters and redundant optics for simultaneous multicomponent operation).

The situation changed dramatically when Fast Fourier Transform (FFT) Processors for LDV signals were introduced. The FFT processors could detect multiple frequencies in a given Doppler burst (within their operating band width) they eliminated the need for redundant optical systems, and multiple processors, for multicomponent measurements.

They also had a much greater capability to discriminate between good and bad signals prior to analyzing them, were able to accurately process much lower signal-to-noise ratio signals, and required far fewer fringe-crossings to analyze a given burst. These last three factors allowed for the use of much smaller diameter laser beams, with much smaller beam-crossing angles (i.e., larger fringe spacings), resulting in the possibility of measuring much closer to solid surfaces than ever before (Fig. 1).

Dennis Johnson of the NASA/Ames Research Center combined the advantages offered by FFT signal processors with a beam-steering probe inserted in the flow to devise a new self-aligning, near-wall LDV approach capable of making direct measurements of the transverse velocity component (Ref. 1). The author applied this new technique to a 2-dimensional, zero-pressure-gradient, flat-plate boundary layer in the High Reynolds Number Pilot Channel at Ames, and was able to make accurate and repeatable measurements of U and uu to within 30 mm of the wall (Ref. 2). The single-frequency accousto-optic modulator (Bragg cell) used to split the laser beam and allow directional discrimination in the original system was then replaced by a dual-frequency Bragg cell, thereby allowing simultaneous 2-component operation, and the measurement of U, V, uu, vv, and uv. (Note that W, ww, and wv could also be measured by rotating the beam-steering probe, but these quantities are either zero or of little interest in a 2D flow).

APPLICATION TO 3D WEDGE FLOW

The next step in the development of the near-wall LDV technique was to employ it in a previously-tested, computationally manageable, 3-dimensional separated boundary layer flow. The 3D Wedge Flow facility in the Mechanical Engineering Department at Stanford University fit that description, and was made available to the author through Dennis Johnson, his NASA Cooperative Agreement Technical Monitor. The flow (Fig. 2) consisted of a 2-dimensional wall boundary layer approaching a right-angle wedge. The resulting lateral and adverse streamwise pressure gradients generated significant spanwise velocities and turbulent stresses, and a large reverse-flow region.

The near-wall LDV was modified further to facilitate measurements in the 3D Wedge Flow. The original system required 9 optical components (2 lenses, 6 mirrors, and the Bragg cell) to be spread out over an optical path length of over 5 meters in order to produce a probe volume with the desired characteristics (size and fringe spacing) and distance from the final focussing lens. And, it still had the undesirable necessity to vary the beam path length when traversing the measurement location. It also was extremely difficult, and time-consuming, to align at the various orientations required to make full turbulent stress-tensor measurements with a 2-component system.

The modified system (Fig. 3) used a fiber optic cable terminated by a very short focal length lens, 2 miniature mirrors, and a negative/positive lens combination to produce the same probe volume, at the same distance, all inside an aluminum tube approximately 1 inch in diameter and 14 inches long. Since the entire tube, containing all of the optics, moved during a traverse, the beam path length always remained constant. The tube was also held in the rotating arm of a mounting device that made changing between optical orientations a literal "5 minute job."

Figure 3a shows the system in top view (i.e., looking in the -z direction) when it is oriented to measure the streamwise and normal components of velocity. Figure 3b shows the same view when the spanwise and normal velocity components are being measured at the same point. A single green beam ($\lambda = 514.5$ nm) enters the dual-frequency Bragg cell and is split into four beams: one at the original frequency, and the other 3 all at slightly different, but accurately known frequencies. (The axis of the four beams is shown as a white dotted line passing through the Bragg cell and tube.) They diverge from one another and expand individually at a constant rate through the tube until they reach a negative focal length lens in the necked-down portion of the tube. The negative lens increases the rates of divergence and expansion until the beams pass through the final (positive) focussing lens, through the tunnel wall, onto the reflective prism of the beam steering probe, and down to the measurement location.

In the u-v orientation, the optical tube, the beam-steering probe, and the measurement point all lie in the z-y plane. In the w-v orientation, they are in the x-y plane. To measure all 3 components of the mean velocity vector, U_i, and all 6 components of the turbulent stress tensor, u_iu_j, measurements were made in these two planes and in two others, at +/- 45^0 to the z-y plane. The latter two were needed to obtain the turbulent shear stress uw.

The streamwise (Fig. 3a) and spanwise (Fig. 3b) velocities and their associated normal turbulent stresses are measured directly. However, because the optical axis is tilted at a small angle, a, to the surface, the measured normal velocity in the u-v orientation contains a contribution from the spanwise component, and a streamwise contribution in the w-v orientation. The tilt angle is needed to make measurements very close to the wall, but then requires that these additional contributions be removed from quantities involving the normal velocity.

RESULTS

Figure 4 shows the streamwise development of mean streamwise velocity (U) profiles in the spanwise symmetry plane (z = 0). In this plane, W, wv, and uw are all theoretically zero. The first point in each profile is taken only 0.003 cm from the wall, and the vertical axis is plotted on a log scale in order to reveal the inner flow. The wedge apex is located at x = 51.8 cm.

The boundary layer at the initial streamwise location (x = 7.6 cm) is not quite in equilibrium, as the flow has just passed through an area contraction, with an associated favorable pressure gradient. From there, the flow encounters the adverse pressure gradient due to the wedge. The flow is retarded a bit in the 15 cm between the first and second streamwise locations, but the shape of the boundary layer stays about the same. However the shape does change in the next 15 cm. The location of separation is clearly between x = 45.7 cm and 46.7 cm, and a significant reverse-flow region is visible just 2 cm farther downstream.

Figure 5 shows profiles of the three turbulent shear stresses at 6.1 cm upstream of the wedge apex and 18.4 cm above the spanwise symmetry plane. Again, the initial data point is at y = 0.003 cm, and the vertical axis is in log scale to better resolve the many near-wall data. There is a large positive correlation between the streamwise and spanwise fluctuations (i.e., uw) very close to the wall; uw reaches a maximum at around y = 0.03

cm. It falls back to zero and becomes negative near y = 0.2 cm, reaching its maximum negative value close to y = 0.4 cm. The uv turbulent shear stress is negative throughout the boundary layer, and reaches its maximum magnitude near y = 1 cm. The wv shear stress is much smaller in general than either uv or wv, but also has positive and negative sections.

FUTURE

The near-wall LDV will next be used to make measurements in the boundary layer and wake of a transonic civil transport wing, in the High Reynolds Channel II facility. It is the type of application that provided the initial impetus for the technique's development. Much of the boundary layer on the wing is less than 1 mm thick. The flow is highly 3-dimensional, and involves significant separation. It is also the type of flow that has been problematic for computations, and for which there are no flow-field data.

If testing on the transonic wing is successful, one can envision a widespread use of the near-wall LDV technique. It offers the potential to obtain critical, and previously unobtainable turbulence data, in a variety of flows, for relatively little cost.

PUBLICATIONS

Johnson, D.A. and Brown, J.D. 1990 A Laser Doppler Velocimeter Approach for Near-Wall Turbulence Measurements. NASA TM-102841

Johnson, D.A. and Brown, J.D. 1995 Further Developments in Near-Wall Laser Doppler Velocimetry. To be published.

Brown, J.D. and Johnson, D.A. 1995 A Near-Wall LDV Investigation of Turbulent Boundary Layer Development in the Spanwise Symmetry Plane of a 3-Dimensional Separating Flow. To be published.

Brown, J.D. and Johnson, D.A. 1995 A Near-Wall LDV Investigation of Turbulent Boundary Layer Behavior in a Separating Flow with Significant Lateral Strain Rates. To be published.

Figure 1: Improved LDV Spatial Resolution with FFT Processing

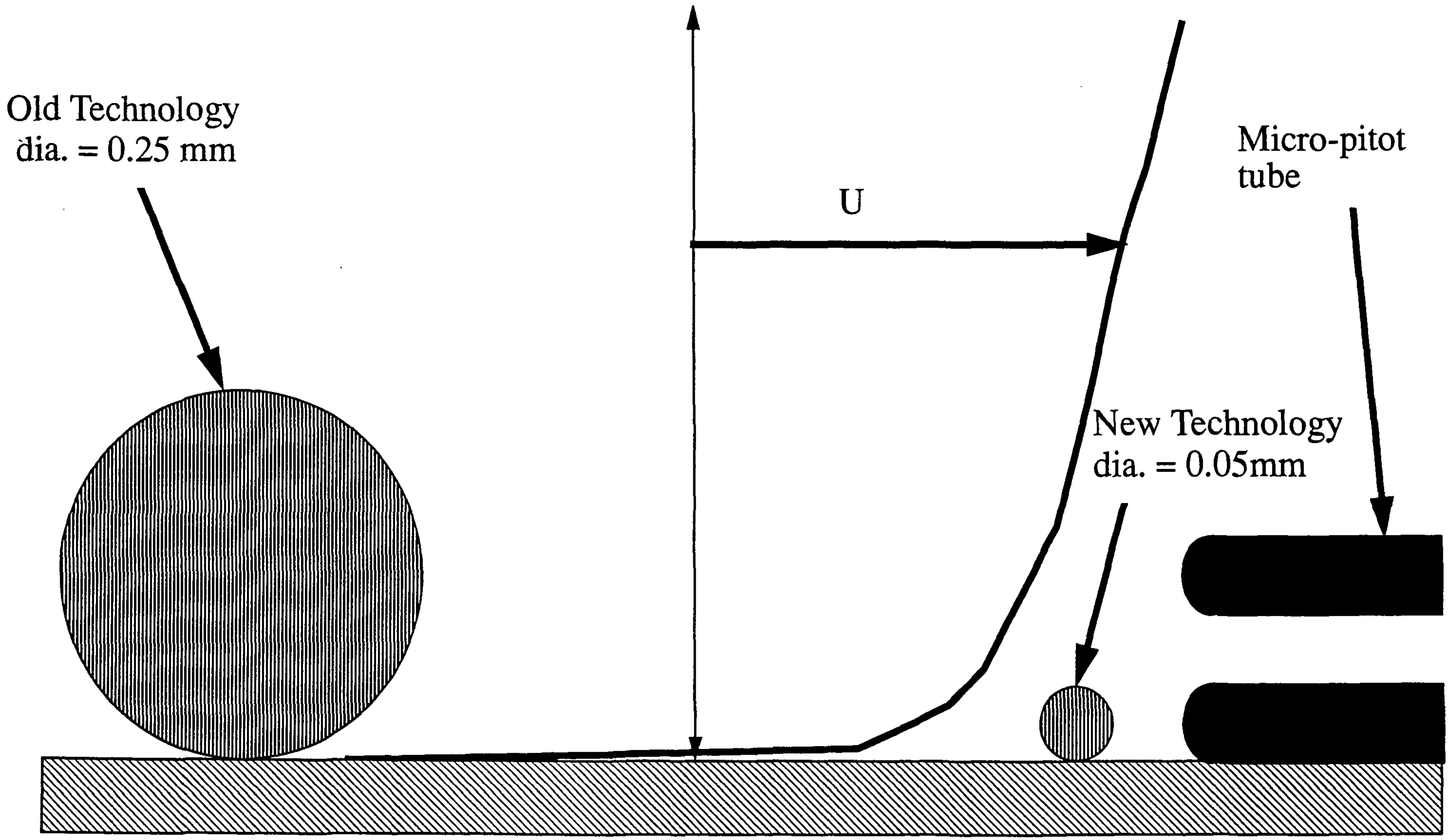


Figure 2: 3D Wedge Flow Test Geometry

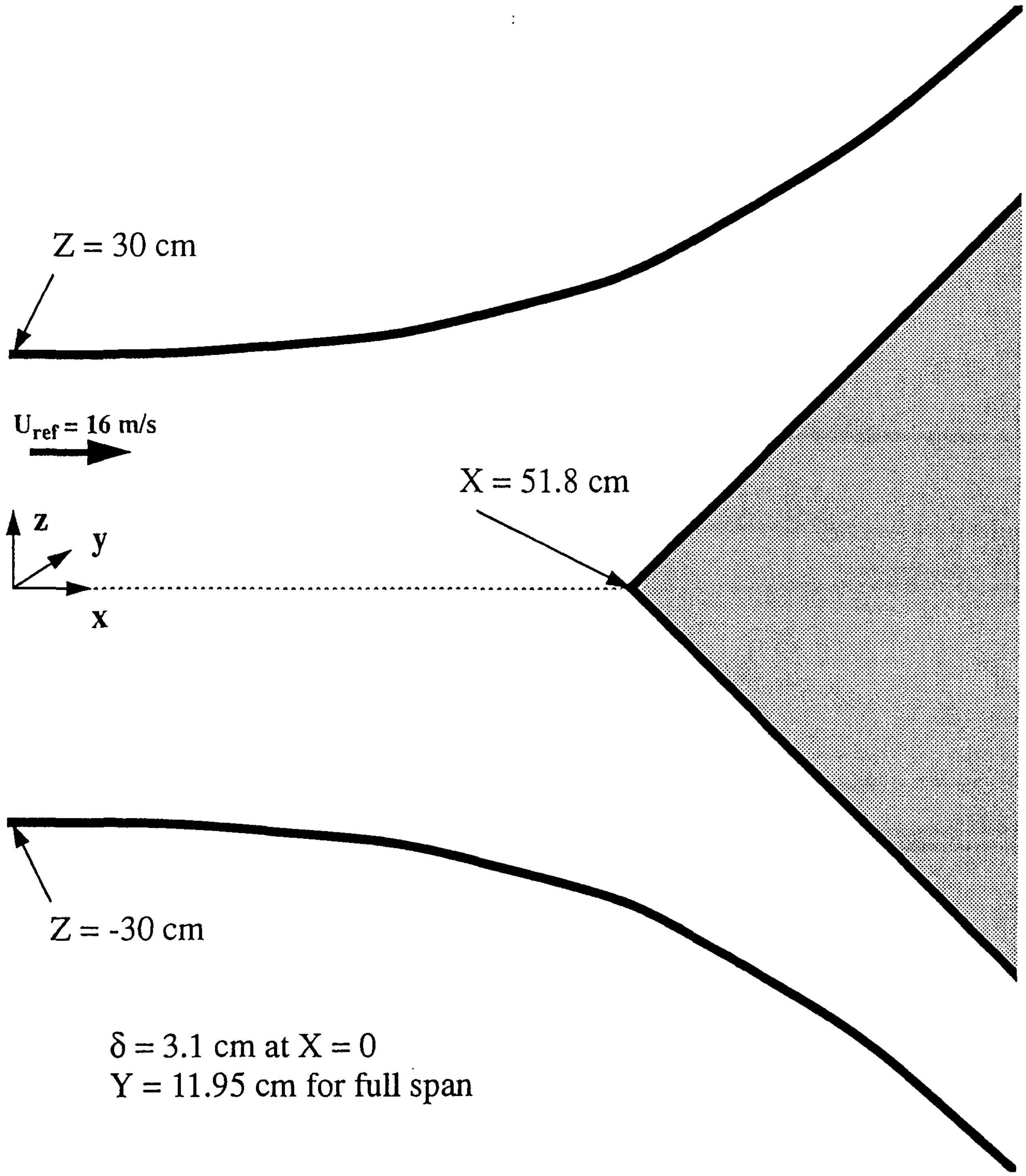
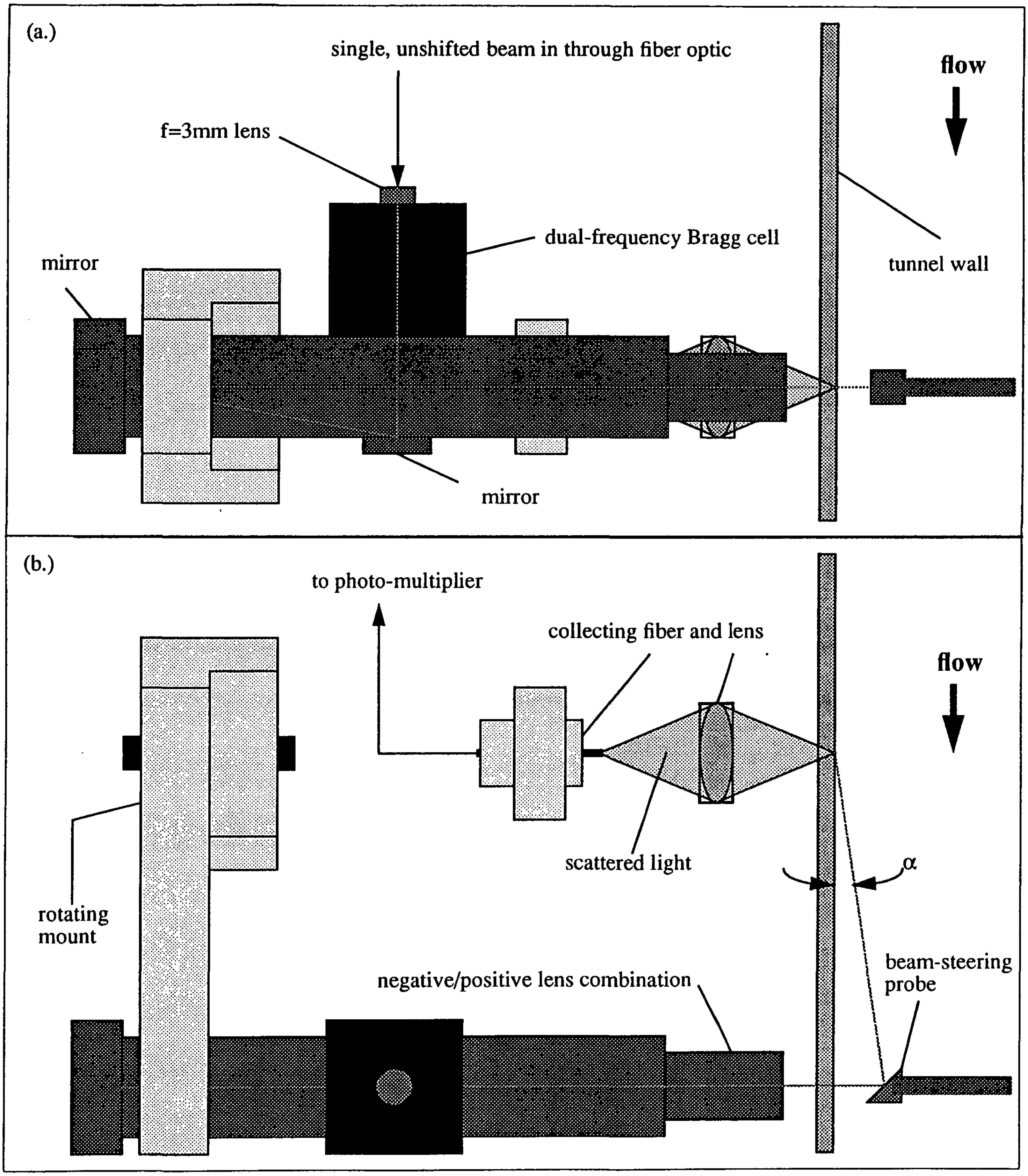


Figure 3: Fiber-Optic Based Near-Wall LDV for 3D Wedge Flow



(a.) u-v orientation, top view (b.) w-v orientation, top view

Figure 4: Mean Streamwise Velocity, 3D Wedge Flow, Centerline (Z = 0)

X = 51.8 cm at Wedge Apex

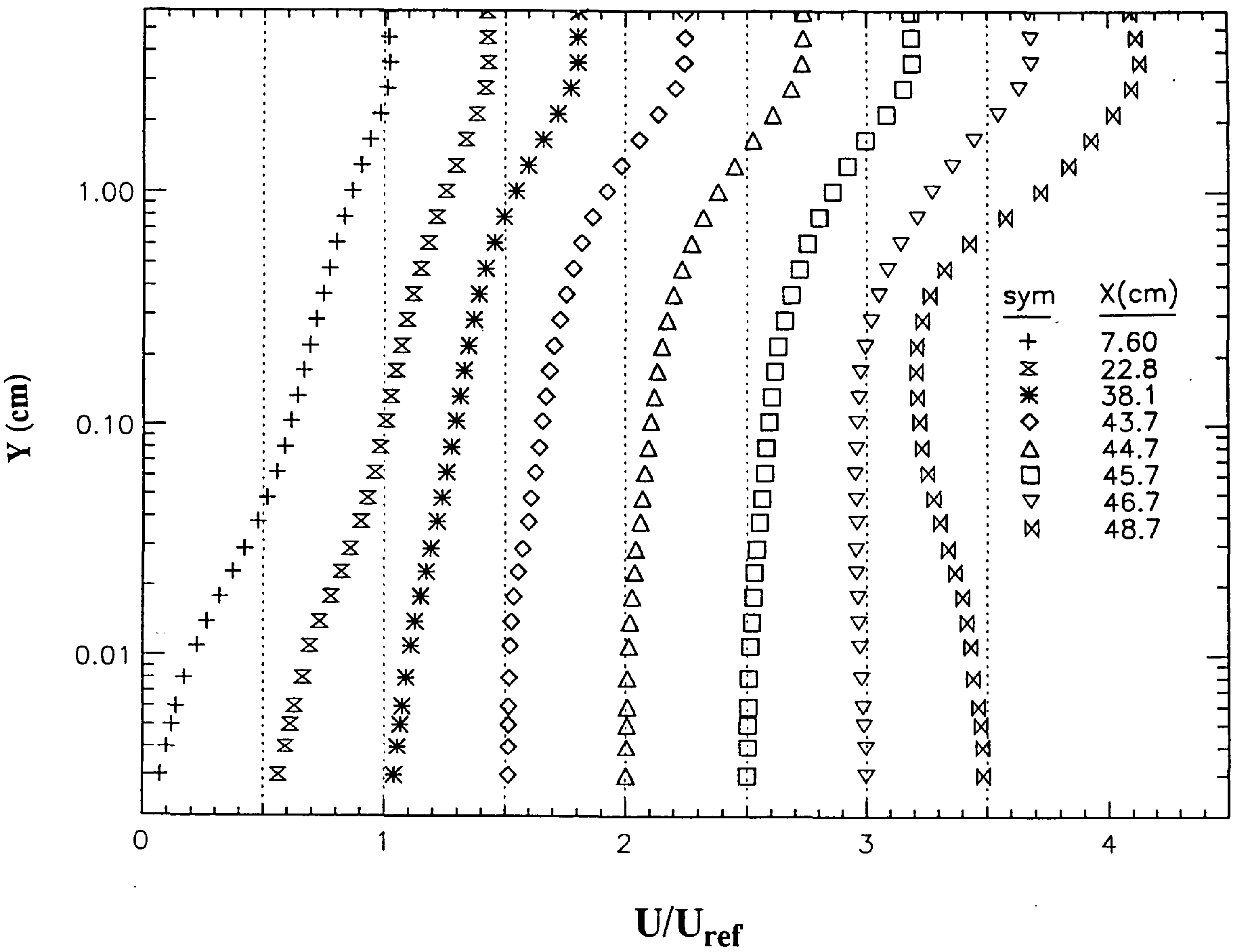
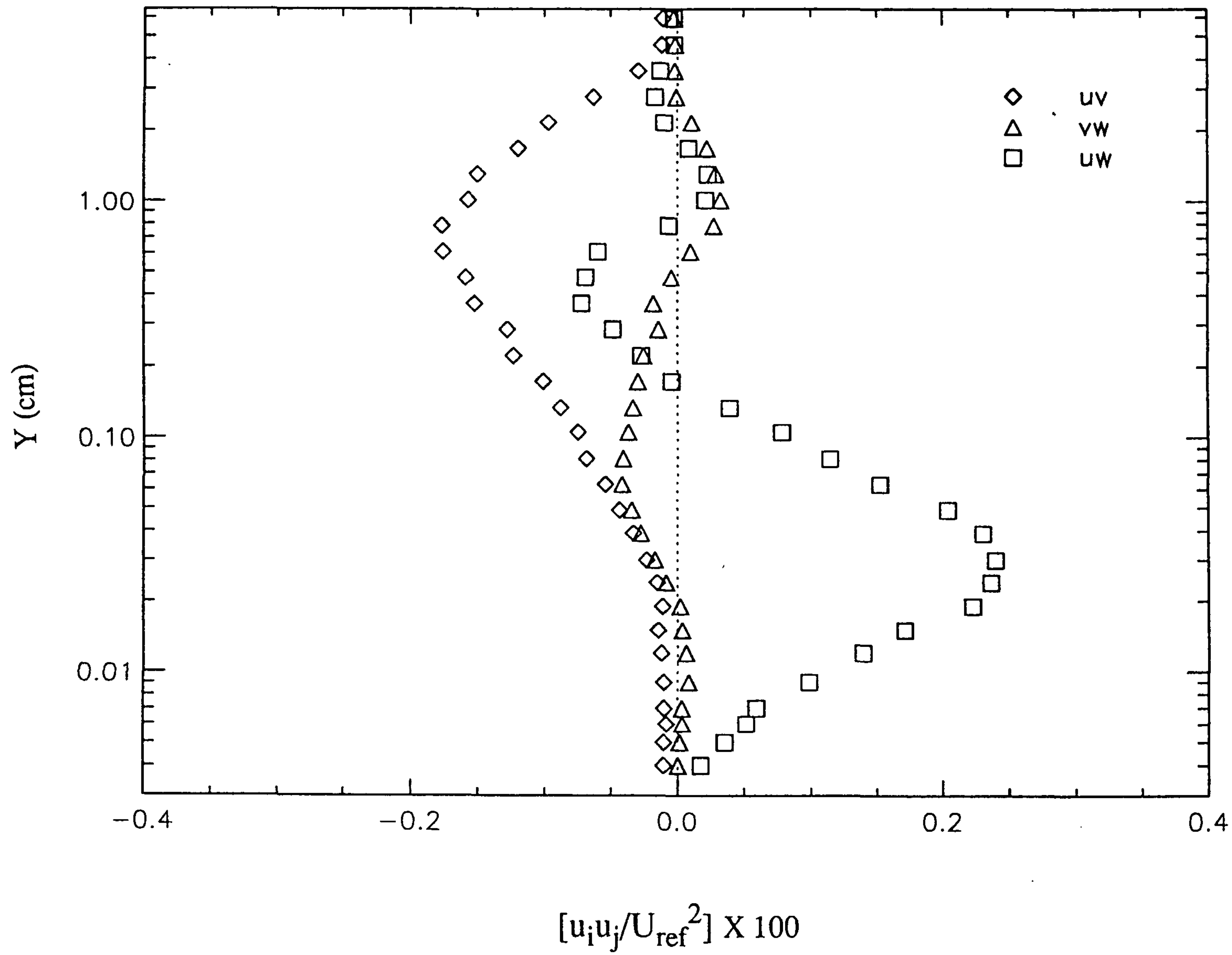


Figure 5: Turbulent Shear Stresses, 3D Wedge Flow, X = 45.7cm, Z = 18.4cm

X = 51.8 cm at Wedge Apex



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15. Supplementary Notes

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16. Abstract

This report describes the development of a new near-wall LDV technique, and its use to measure the full turbulent stress tensor in a highly three-dimensional separated boundary layer flow.

Laser Doppler velocimetry, with small diameter laser beams allowing small beam-crossing angles (i.e., larger fringe spacings), was used, resulting in measurements close to solid surfaces. Dennis Johnson of NASA/Ames combined the advantages offered by FFT signal processors with a beam-steering probe inserted in the flow to devise a new self-aligning, near-wall LDV approach capable of making direct measurements of the transverse velocity component. This new technique was applied to a 2-D, zero-pressure-gradient, flat-plate boundary layer in the High Reynolds Number Pilot Channel at Ames. Accurate and repeatable measurements of U and uu to within 30 mm of the wall were obtained.

Next, the near-wall LDV technique was employed in a 3-D separated boundary layer flow, consisting of a 2-dimensional wall boundary layer approaching a right-angle wedge. The resulting lateral and adverse streamwise pressure gradients generated significant spanwise velocities and turbulent stresses, and a large reverse-flow region.

The near-wall LDV was modified further to facilitate measurements in the 3D Wedge Flow.

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