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WAKE MEASUREMENTS IN A STRONG ADVERSE PRESSURE GRADIENT

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Abstract

The behavior of wakes in adverse pressure gradients is critical to the performance of high-lift systems for transport aircraft. Wake deceleration is known to lead to sudden thickening and the onset of reversed flow; this 'wake bursting' phenomenon can occur while surface flows remain attached. Although 'wake bursting' is known to be important for high-lift systems, no detailed measurements of 'burst' wakes have ever been reported. Wake bursting has been successfully achieved in the wake of a flat plate as it decelerated in a two-dimensional diffuser, whose sidewalls were forced to remain attached by use of slot blowing. Pitot probe surveys, L. D. V. measurements, and flow visualization have been used to investigate the physics of this decelerated wake, through the onset of reversed flow.

Introduction/Literature Review

The performance of an aircraft is strongly affected by the performance of its high-lift system. An example of a 150 passenger transport airport given in reference [4] shows that a 5% increase in takeoff lift/drag ratio results in a 15% increase in payload or an 11% increase in range. Also a 5% increase in maximum lift at landing gives a 20% increase in range and a 3 knot decrease in approach speed for a significant reduction in landing length. Since cost, weight, and serviceability are influenced by the high-lift system, performance improvements must result from advancements in aerodynamics, not increased system complexity.

Some of the difficulties associated with high-lift aerodynamics are apparent in figure 1, similar to one in reference [4], which includes only two-dimensional effects. Multi-element slotted airfoils can have regions of interaction between upstream element wakes and boundary layers on downstream elements. If flow turning angles become significant, such 'confluent' boundary layers can be accompanied by high adverse pressure gradients. When the low energy flow of a wake encounters the adverse gradient created by a downstream element, the wake decelerates and may even reverse. This type of off-the-surface flow reversal or 'bursting' is discussed in reference [7], and is believed to be responsible for the 'reverse' Reynolds number effects described in reference [4]. Klausmeyer et al. also discuss reverse Reynolds number trends in reference [3]. This is one of several papers which speculate that wake bursting limits high-lift performance.

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In his well known review of high-lift aerodynamics, Smith provides a simple analysis using Bernoulli's equation to show that wake reversal is possible, citing an analysis due to Gartshore [2,7]. Smith points out that according to Gartshore's analysis, boundary-layer separation is more likely to occur than 'off-the-surface' separation. He concludes that more study of wake bursting is desirable. Wake reversal does appear to have been captured in a study by Braden et al., who measured the flow field around a GAW-1 multi-element airfoil, though the authors do not discuss the issue [1]. A few other studies, outlined in reference [6], have noted the presence of wake bursting, but none of these have examined it specifically.

Petrov may be the only researcher who has performed a study on wake reversal [5]. In this experiment, a tufted rectangular wing was tested using endplates, with various configurations of leading and trailing edge devices. Tufts were also used in the free-stream, attached to rods mounted normal to the surface of the airfoil near mid-span. For the two-slot flap, '*... it was found...that the reduction in the rate of lift gain* $C_{L\alpha}$ *... is associated with the appearance of a region of flow reversal, situated at some distance from the wing surface a distance commensurable with the thickness of the air stream passing through slots in the flap. At the same time, the flow directly on the wing and flap surfaces does not separate. The flow reversal region ... becomes thicker with increasing flap angle and angle of attack* [5].' At larger flap deflections, the flow over the flap separated. Off-the-surface separation was observed to limit the maximum obtainable lift. Also cause for concern was its effect on the lift curve slope, $C_{L\alpha}$. Increasing the deflection of a trailing edge flap after wake reversal has occurred may increase drag more than lift. The resulting loss in L/D could force pilots to increase engine power on approach, hampering efforts to reduce airport noise. The above observations made by Petrov raise questions about some important issues which merit further study.

It is clear there has been little detailed analytical or experimental research into wake bursting, although it seems to have become generally accepted that it is an important high-lift problem. Some of the references cited above have observed wake bursting in the flow field around a high-lift system, but none have made detailed mean or turbulence measurements, or used smoke flow visualization to investigate this particular phenomenon. If information of this type was available, it might lead to a turbulence model for wakes in adverse pressure gradients, or at least help to predict when wake bursting is likely to occur. Incorporating such empirical information into high-lift design codes could significantly benefit the next generation of transport aircraft.

Experiment

Because of the interest in wake bursting, it was decided to investigate this effect specifically, on a fundamental level. A simple 6 foot long flat plate was used to generate a wake, and a variable angle diffuser was built behind it to create an adverse pressure gradient (see figure 2). The flat plate was mounted in a 12" x 18" open return subsonic wind tunnel, which for this study was operated at 50 ft/s (Re = 2 million). Since the boundary layers on the diffuser walls separated before the wake reversed, tangential blowing slots, driven with compressed air, were incorporated into the diffuser walls (see figure 3). Blowing kept the wall boundary layers attached at diffuser angles large enough to reverse the wake of the flat plate.

Pressure and L.D.V. velocity measurements were used to quantitatively investigate this flow-field. For the pressure measurements, a pitot-static probe, connected to a Validyne digital pressure transducer, was scanned with a stepper motor driven, computer controlled x-z traverse. Pressure data were acquired with a 12 bit PC data acquisition board. A single component argon-ion forward scatter system was used to make the L.D.V. measurements. It too was traversed automatically on a motorized platform (see figure 4).

To gain further insight into the physics of the flow, nichrome wires were hung vertically at several locations in the diffuser. When an electric current was run through one of these wires, it would heat very rapidly. Dripping kerosene or propylene glycol down the wire before heating it would send a burst of smoke into the flow at a given location. A pulsed light sheet from a Lumonics Nd:YAG laser illuminated the flow, while a Sony XC-77RR video camera recorded the image. These images were digitized with an EPIX frame grabber board for further study.

Discussion

With no adverse gradient, the flow field behind the plate formed an ordinary two-dimensional turbulent wake, as indicated by the particle image velocimetry plot in figure 5. When the diffuser was opened between 0 and 6 degrees (half angle), the velocity defect in the center of the wake grew in magnitude and width, due to the adverse gradient (see figures 6 & 7). L.D.V. mean velocity measurements agreed well with pitot probe measurements, and turbulence data corresponded to traditional flat plate wake profiles (see figure 8) [8]. L.D.V. surveys at the trailing edge and mid-diffuser locations further demonstrated wake sensitivity to prolonged exposure to the negative gradient (see figures 9-12), while scans in the spanwise direction indicated that the flow was uniform in the middle region of the diffuser. It is clear from the L.D.V. measurements that increases in diffuser angle have a less dramatic effect as 6 degrees is approached. This is due to separation of the boundary layers on the diffuser walls. However, with the aid of diffuser blowing, the boundary layers remained attached, while pitot probe surveys indicated that the wake was likely reversed by a diffuser half-angle of 11 degrees (see figure 13). The high velocity regions near the walls are due to high speed blowing from the tangential slots. Though this plot suggested reversal at the end of the diffuser, tufts on the trailing edge of the flat plate showed that the wake was clearly attached there, so bursting was occurring somewhere in the diffuser.

To more precisely determine the point where the reversed flow began, smoke wires were used with a pulsed YAG light sheet directed up the tunnel centerline. In figure 14, smoke is seen to travel downstream from the 'smoke wire' everywhere but in the wake, where the smoke is carried upstream. Smoke wire photography carried out at different locations showed that the bursting point was about halfway up the diffuser. Spanwise photography showed smoke being carried to and from the diffuser side walls, meaning the reversed case was also a three dimensional flow-field.

Conclusions and Future Plans

Wake bursting has been isolated and reproduced in a subsonic facility, and systematically investigated with several techniques. Preliminary results have demonstrated that the facility is capable of taking a wake up to and beyond the bursting point. By the time of the AIAA meeting next summer, it should be possible to make several important improvements to this facility. Larger blowing slots are being constructed, which will decrease pressure losses, reducing the demand for compressed air and extending run time. The addition of a Bragg cell to the L.D.V. system will improve the quality of measurements made in the reversed wake. Blowing slots will also be added to the side walls, to reduce boundary layer separation during wake reversal. This is necessary, since they are subjected to the same adverse pressure gradient as the moveable panels. These refinements will allow detailed, systematic measurements to be made on a flow field of great importance to high-lift aerodynamics.

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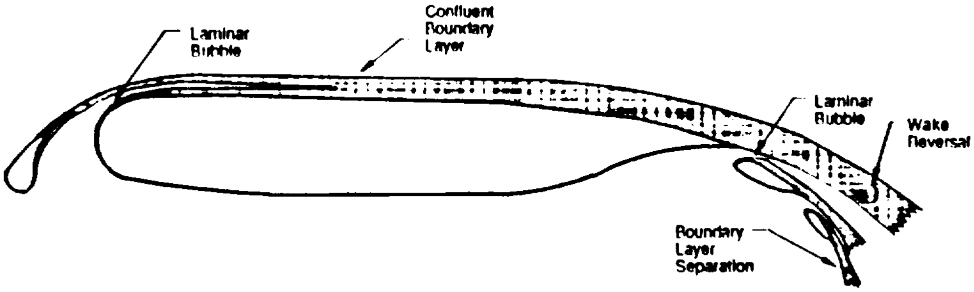

Figure 1. Flow over a Two-Dimensional High Lift Airfoil System.

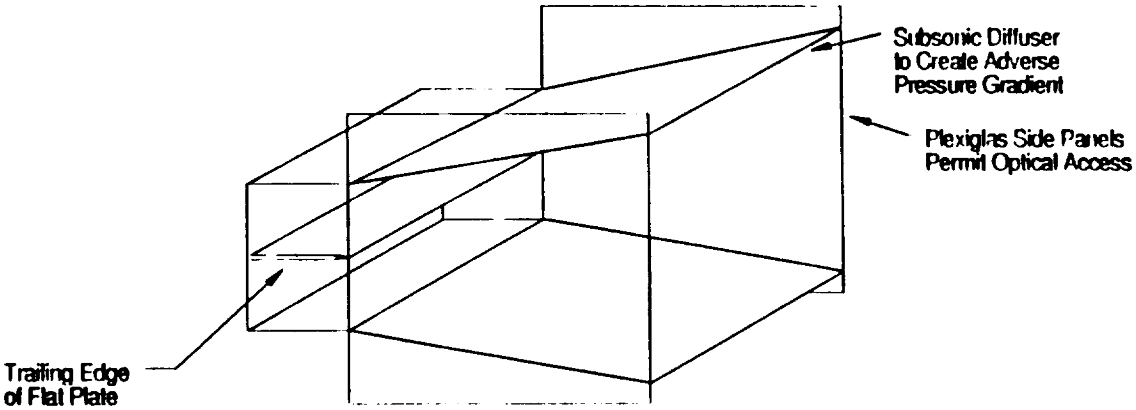

Figure 2. Diffuser Used to Create Adverse Pressure Gradient.

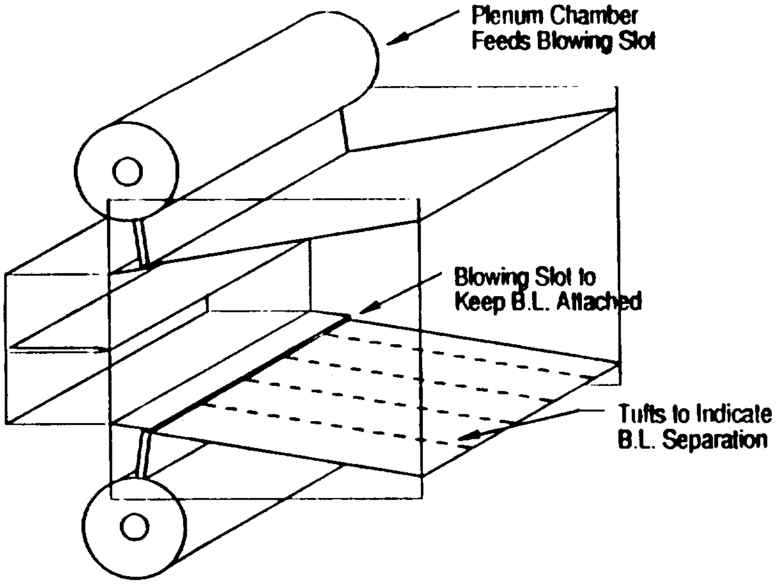

Figure 3. Diffuser with Active Boundary Layer Control to Prevent Separation.

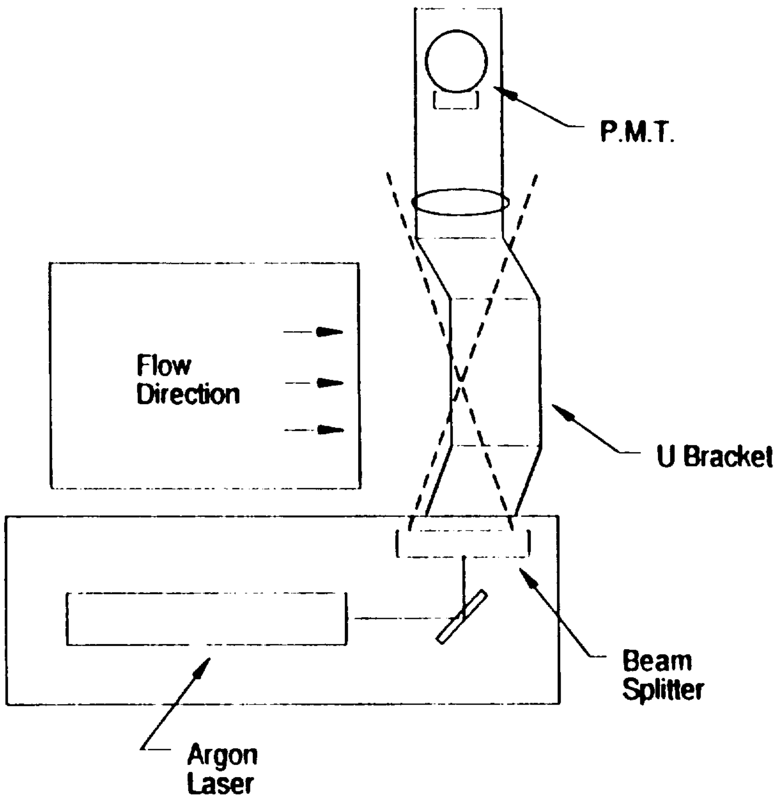

Figure 4. Top View of Forward Scatter L. D. V. System.

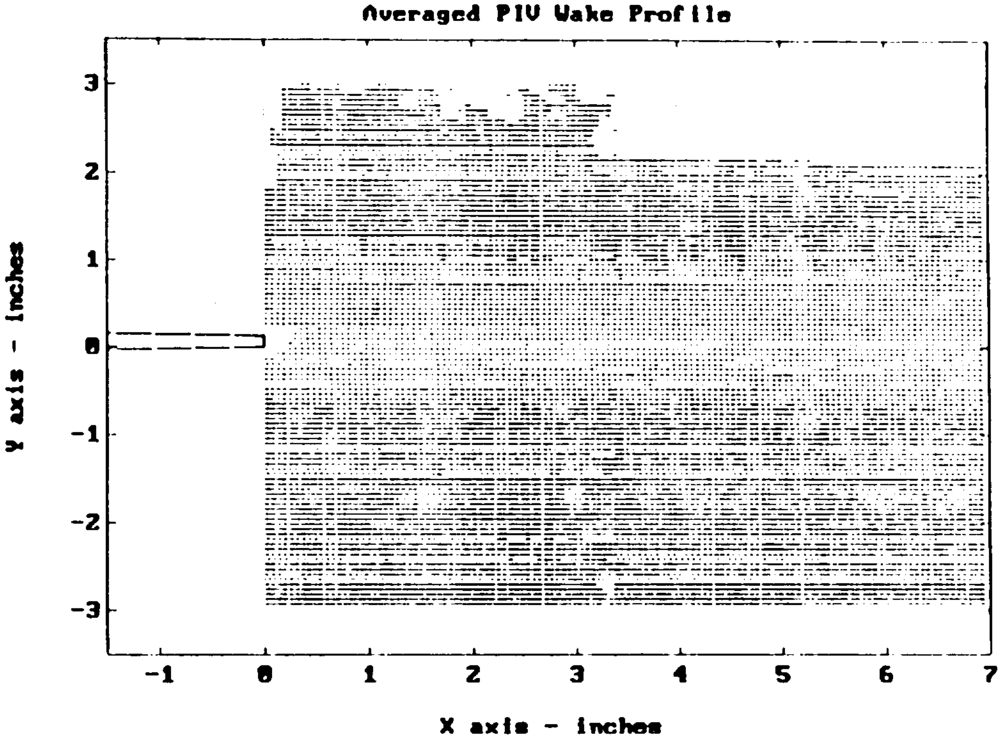

Figure 5. P. I. V. Photograph of Wake without Diffuser.

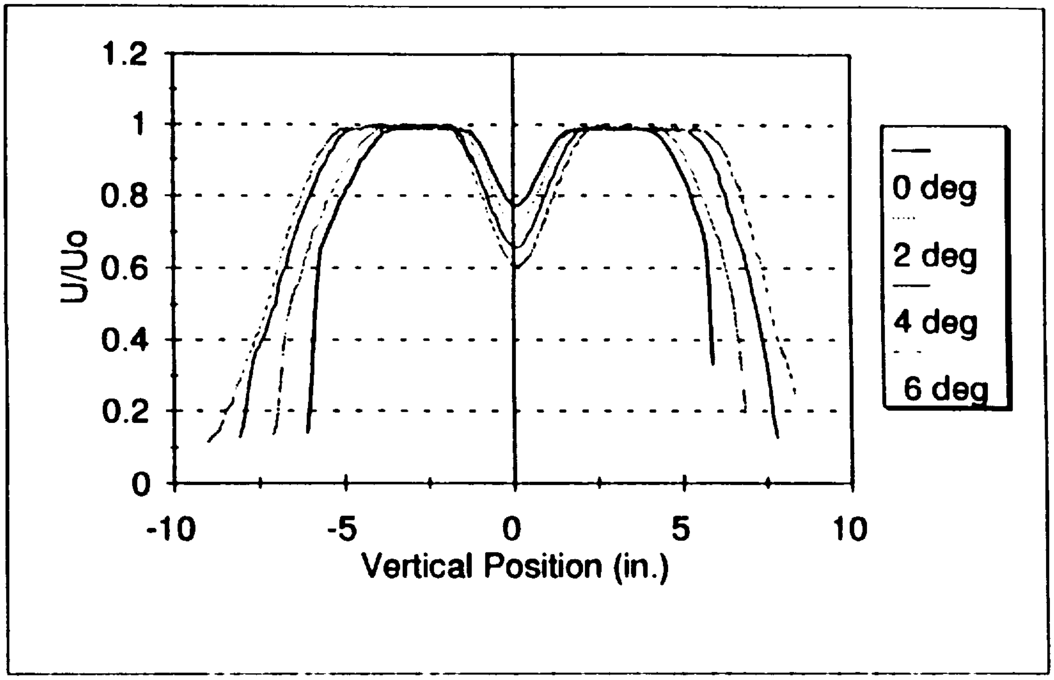

Figure 6. Mean Velocity Measured with L. D. V. at End of Diffuser.

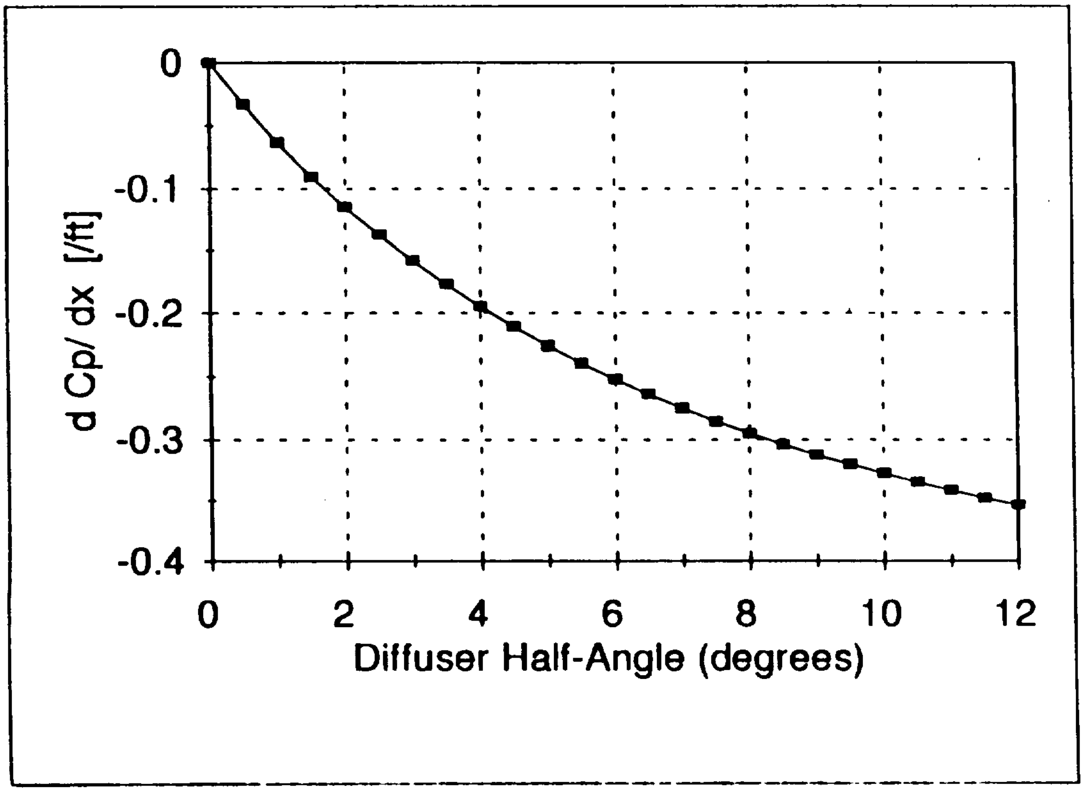

Figure 7. Approximate Pressure Gradient Created by Diffuser.

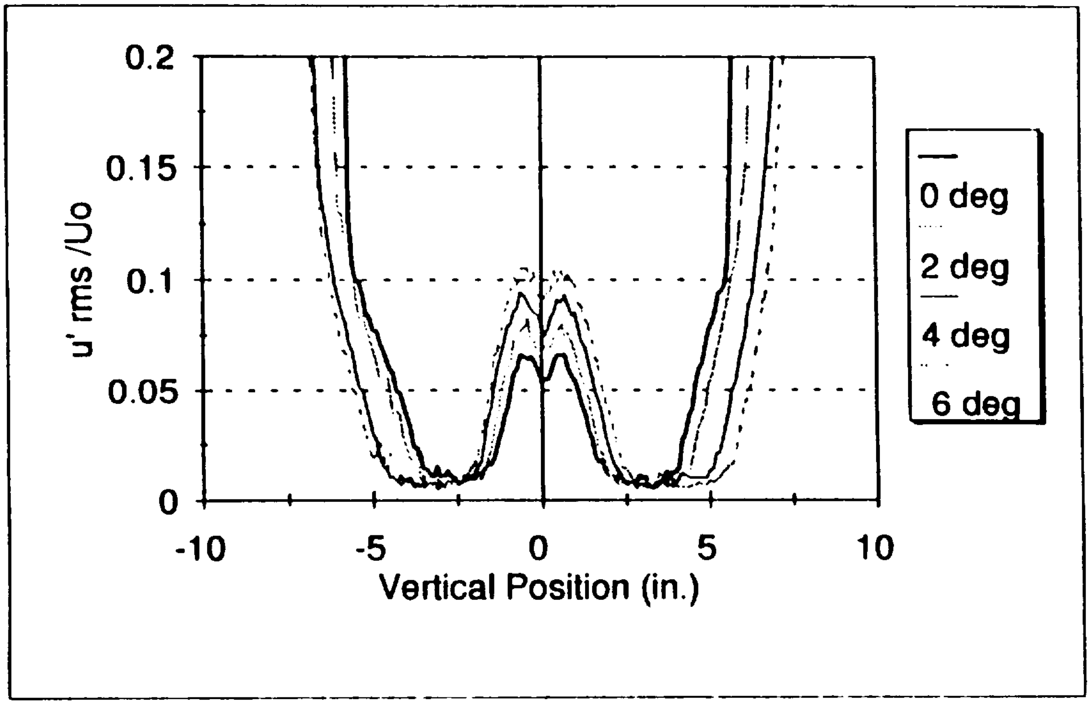

Figure 8. Turbulence Measured with L. D. V. at End of Diffuser.

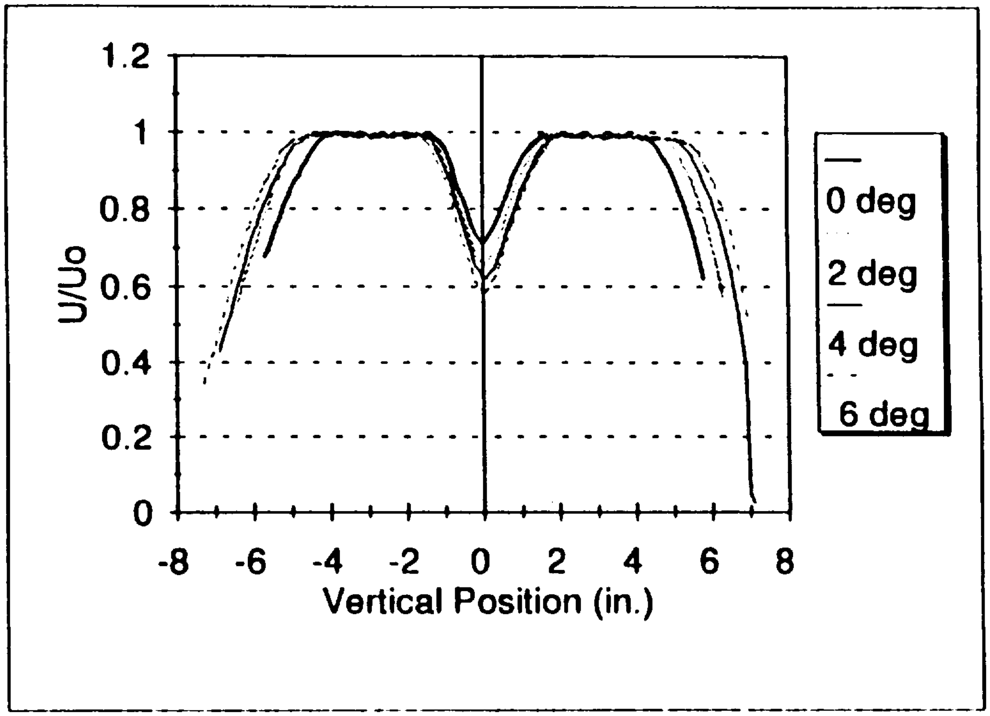

Figure 9. Mean Velocity Measured with L. D. V. at Middle of Diffuser.

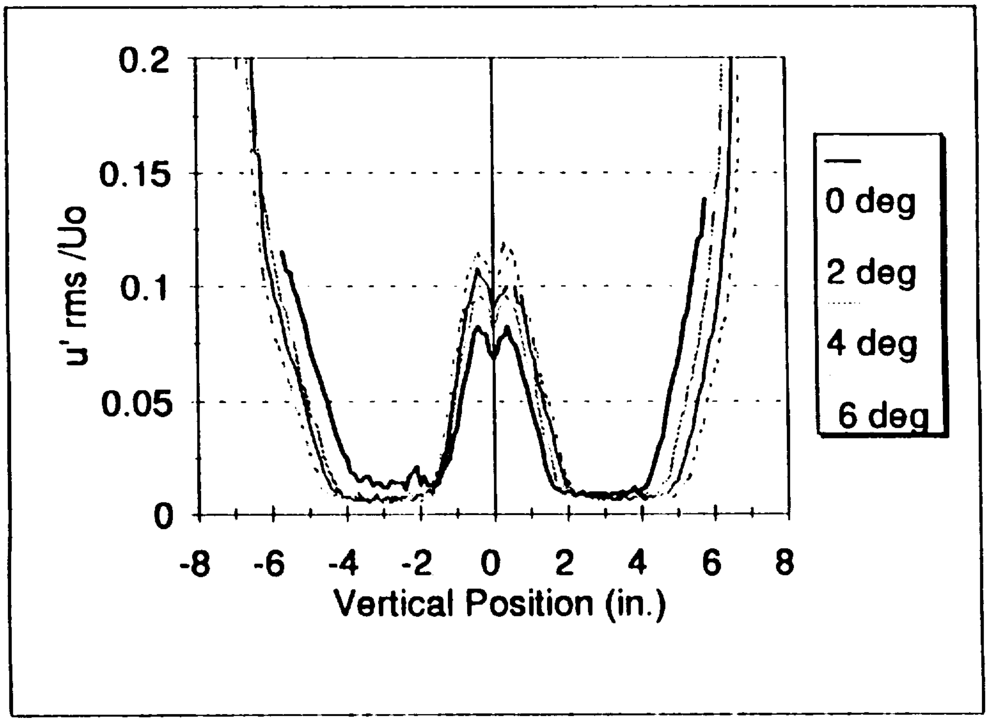

Figure 10. Turbulence Measured with L. D. V. at Middle of Diffuser.

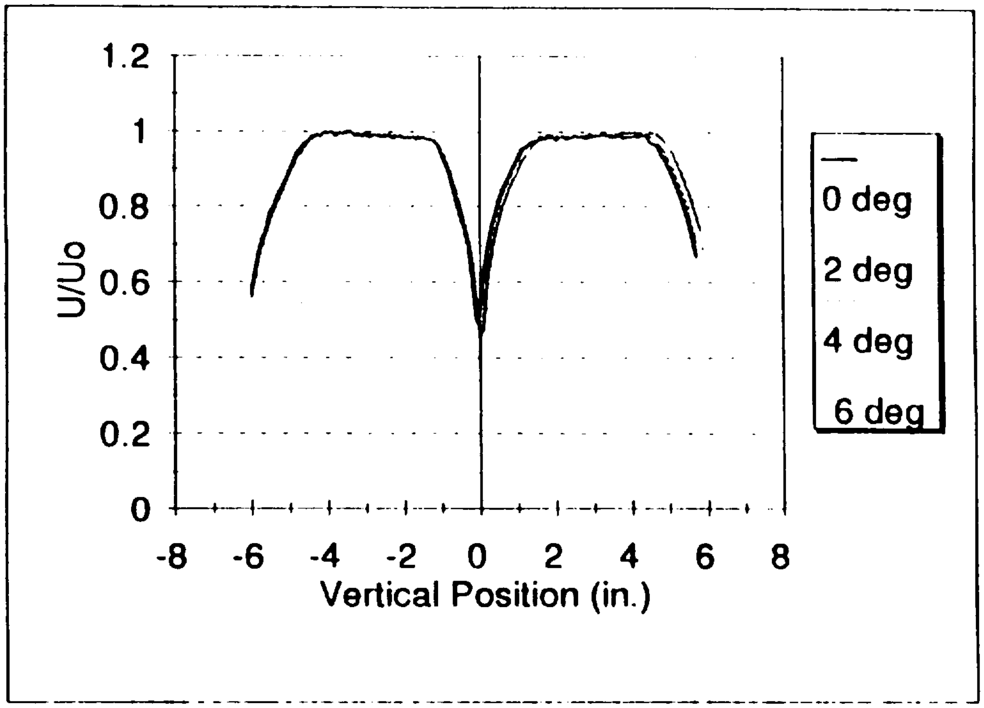

Figure 11. Mean Velocity Measured with L. D. V. at Trailing Edge.

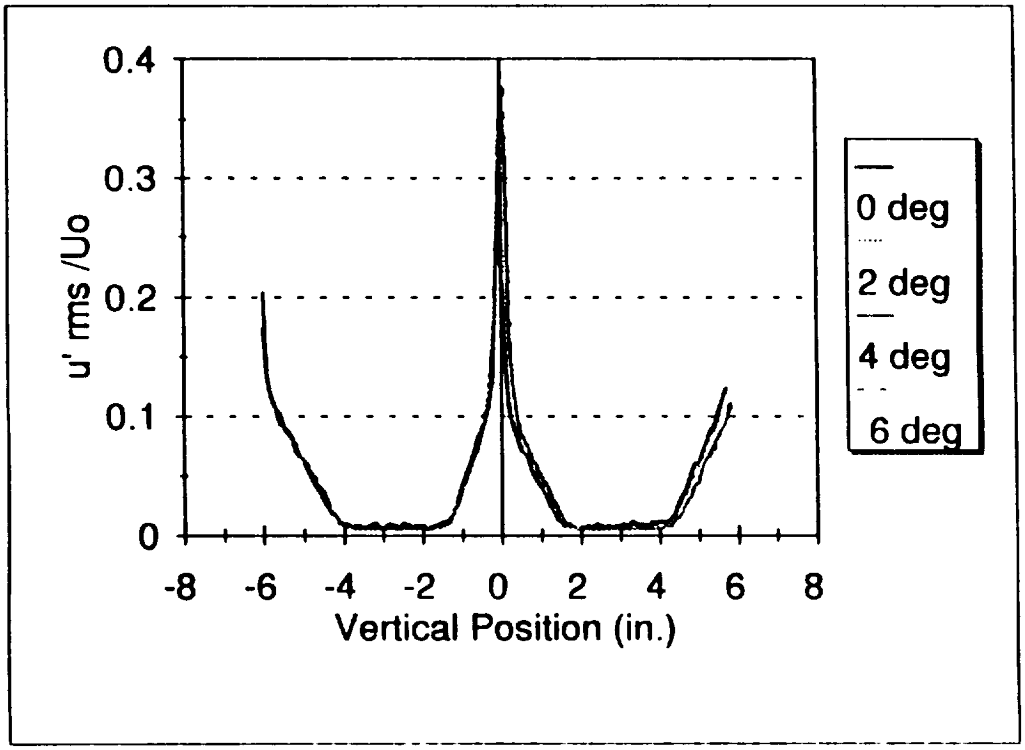

Figure 12. Turbulence Measured with L. D. V. at Trailing Edge.

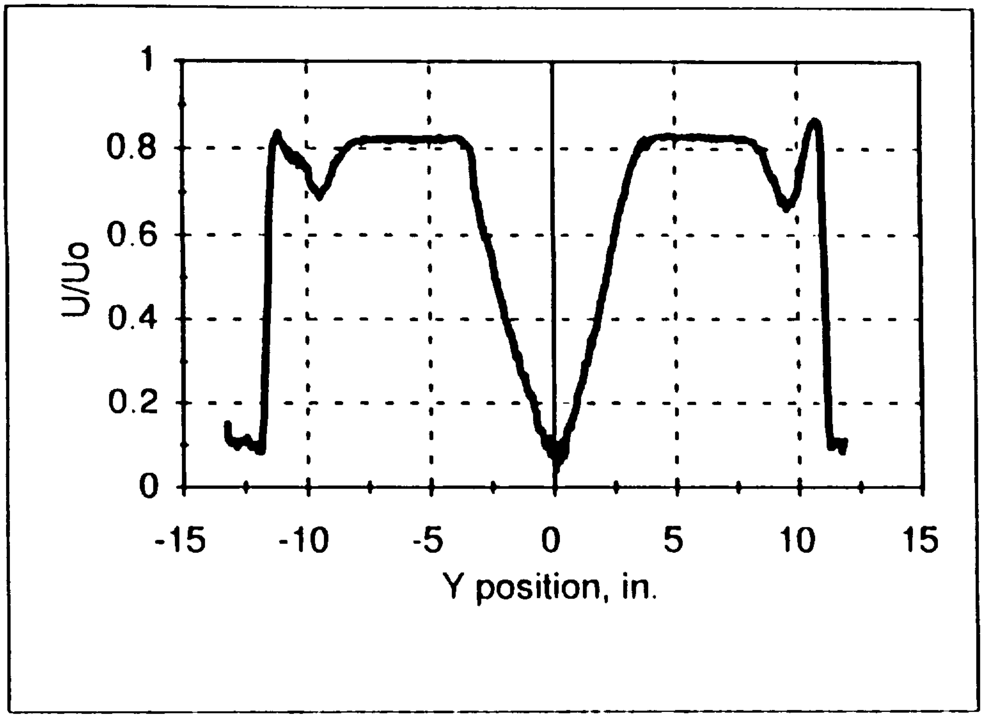

Figure 13. Pressure Survey of Reversed Wake Flow at End of Diffuser.

Figure 14. Photograph of Reversed Wake Flow.