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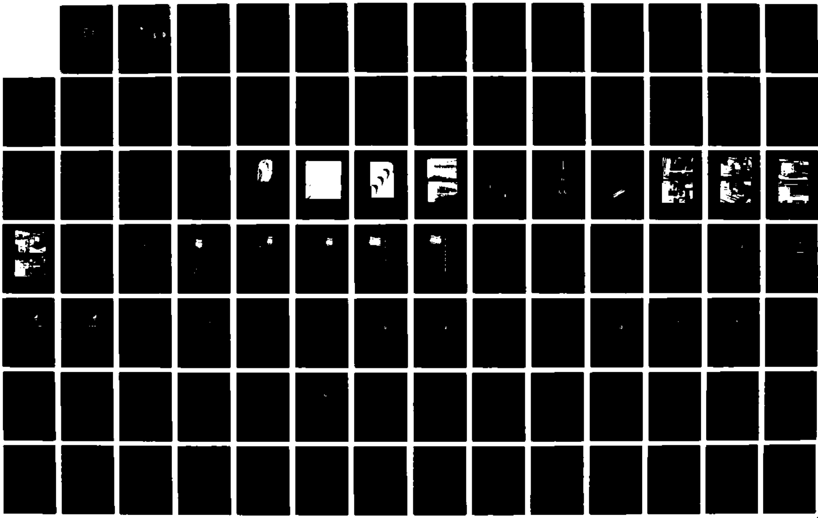

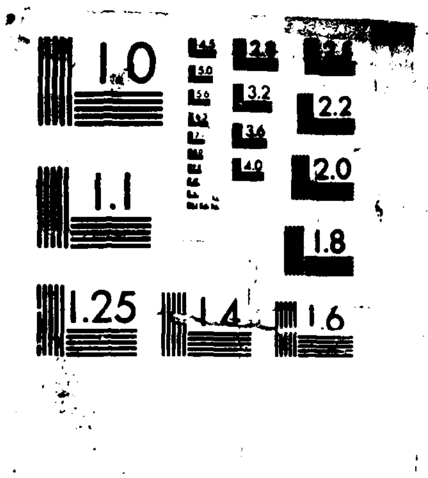

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

STUDY OF VORTICES
EMBEDDED IN BOUNDARY
LAYERS WITH FILM COOLING

by

David L. Evans

March 1987

Thesis Advisor Phillip M. Ligrani

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The results show that the embedded vortices completely dominate the flow field in boundary layers with film cooling. This is indicated from the plots of V, V_x, and P_o which show the effects of film cooling to be completely decimated in the vicinity of the vortex.

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A boundary layer profile was conducted to verify the calibration of the pressure probe, measurement procedures, and velocity computations. The results show expected boundary layer behavior with a small V_y and V_z component.

Study of Vortices Embedded in Boundary Layers with Film Cooling

by

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A boundary layer profile was conducted to verify the calibration of the pressure probe, measurement procedures, and velocity computations. The results show expected boundary layer behavior with a small V_y and V_z component.

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I. INTRODUCTION

The increasing need for greater efficiency in gas turbine engines has resulted in higher turbine inlet temperatures. Consequently, combustor liners and turbine blading are subjected to greater amounts of thermal stress, thermal fatigue, and creep. At present, gas turbines, such as those associated with military applications, have inlet temperatures as high as 1800 - 2000 degrees C (3270 - 3632 F) with pressures of 40 atmospheres.

Turbine parts may be protected from heat loads resulting from exposure to gas at high temperatures by using a coolant within turbine passages and along turbine surfaces. Convection cooling, impingement cooling, transpiration cooling, and film cooling are used for this purpose. Although it is possible for the cooling medium to be a substance such as liquid water or Freon - 12, most gas turbine arrangements utilize engine air bled off from the compressor and rerouted to the turbine nozzles and blading. With film cooling, compressor air is ejected from surfaces of blades and vanes. The film coolant then protects metal surfaces by forming a protective insulating film between the blades and the mainstream, and by acting as a heat sink.

The flow through a turbine cascade is extremely complex. Efforts to analytically model the flow are successful only when the fluid is considered to be inviscid. When the effects of viscosity are included, the analysis is much less effective [Ref. 1]. Because of the difficulty involved in analytical representation of the viscous portions of cascade flows, much of the work in this area is experimental in nature.

Flow visualization studies by Herzig, et al., [Ref. 2] were among the first to show the complexity of flow within the cascade. Flow visualization studies by Langston, et al., [Ref. 3] and Marchal and Sieverding, [Ref. 4] also show the detailed development and complexity of the flow through the turbine cascade. More recently, Sieverding and Van Den Bosche, [Ref. 5] have used color smoke-visualization to study the evolution of flow in cascades.

Figure 1.1 from [Ref. 6] shows the various secondary flows associated with flow in turbine cascades. As the inlet boundary layer approaches the blade's leading edge, a horseshoe vortex is formed. The point at which this formation occurs is the saddle point which is clearly shown in Figure 1.2 from [Ref. 4]. One leg of the horseshoe vortex moves initially near the side of the blade, and then through the blade passage where it is referred to as the passage vortex. In cascade flow, the passage vortex is composed of 1) fluid from the pressure side leg of the horseshoe vortex, 2) the crossflow from the endwall boundary layer, and 3) entrained fluid from the mainstream flow, [Ref. 7]. As the passage vortex continues through the cascade, it is forced by the pressure gradient to the opposite side of the passage near the suction side of the adjacent blade. This shift is clearly shown in Figure 1.3 from [Ref. 2]. The second leg of the horseshoe vortex follows the suction side of the blade and has a sense of rotation opposite to that of the pressure side vortex. This vortex moves away from the corner and is generally believed to be smaller in size than the passage vortex. As can be seen from Figure 1.4 from [Ref. 8] the passage vortex makes approximately one rotation as it passes through the cascade. In Figure 1.1 the number of revolutions has been exaggerated for clarity.

The objective of this thesis is to study the effects of embedded vortices on a film cooled turbulent boundary layer. In order to understand the effects that this complex flow field has upon heat transfer, vortex characteristics and their interaction with surrounding flow must be understood. In this study, a five-hole pressure probe is used to measure vortex characteristics.

Extensive procedures for calibration and qualification of the five-hole pressure probe, and its use in measuring three-dimensional flows are first discussed. Results of six different test are then given: 1) a baseline measurement in a developing boundary layer, 2) a boundary layer with film cooling only at a freestream velocity of 15m/s, 3) a boundary layer with a single embedded vortex and without film cooling at a freestream velocity of 15 m/s, 4) a boundary layer with embedded vortex and film cooling at a freestream velocity of 15 m/s, 5) a boundary layer with an embedded vortex and no film cooling at a freestream velocity of 20 m/s, and 6) a boundary layer with embedded vortex and film cooling at a freestream velocity of 11 m/s. Cases 3, and 4 provide the most informative results of the study; cases 5 and 6 are incidental.

II. EXPERIMENTAL APPARATUS

A. WIND TUNNEL

The wind tunnel pictured in Figure 2.1 is now described. It is an open-circuit blower tunnel used to provide uniform flow at the nozzle exit.

1. Description

The wind tunnel is designated the NPS Shear Layer Research Facility (SLRF) and was built by Aerolab. It is designed to provide uniform flow with a minimum amount of turbulence intensity. It is designed with numerous pressure taps and four 38 x 20.3 cm (15 x 8 in.) access ports along each of the of the side walls. The height of the top wall is adjustable to permit changes in the pressure gradient along the length of the test section. Additionally, the top wall contains numerous instrument ports for the measurement of various flow characteristics.

The air speed through the tunnel can be adjusted from 5 m/s to 40 m/s. The blower exit slips into the inlet end of the wide-angle diffuser with 1.6 mm of clearance so that the fan is isolated from the body of the wind tunnel. The diffuser inlet contains a filter and nozzle. The test section is 3.048 m (10 ft.) long and 0.6096 m (2 ft.) wide. The top is fabricated from Lexan sheet (4.76 mm thick), continuously sealed with neoprene along the edges. The tunnel's bottom wall consists of one 1.2192 m (4 ft.) long and three 0.6096 m (2 ft.) long removeable and replaceable sections. These sections are all 0.6096 m (2 ft.) wide and are sealed with "O" rings around the sides. Further discussions of the wind tunnel are contained in [Ref. 9] and [Ref. 10: p. 38].

2. Qualification and Performance

Extensive qualification test of the Shear Layer Research Facility were conducted by Ligrani, [Ref. 11]. Results show that the variation of total pressure at the exit plane of the nozzle is less than 0.4% at 26 m/s and 34 m/s. Mean velocity varies less than 0.7% for the same mean freestream speeds. From five-hole pressure probe measurements, the velocity angle deviation is nowhere greater than about 0.6 degrees at the nozzle exit plane.

Profile measurements of the mean velocity and longitudinal turbulence intensity in the turbulent boundary layer developing at 20 m/s indicate normal, spanwise uniform behavior. For this qualification test, and all results which follow, the boundary layer was tripped near the exit of the nozzle with a 1.5 mm high strip of tape. Total pressure measurements along the test section surface at the nozzle exit were uniform within 0.5% indicating spanwise uniform skin friction.

Freestream turbulence intensity was measure to be 0.00085 (8.5 one - hundredths of one percent or .085 precent) at 20 m/s increasing to 0.00095 at 30 m/s.

B. INJECTION SYSTEM

Ordinarily, the injection system provides film coolant at temperatures above ambient. The freestream air is at ambient temperature; therefore, the heat transfer would then be in a direction opposite to that which occurs in gas turbines. The coolant is injected into the boundary layer through a single row of injection holes. The injection holes are scaled relative to boundary layer thickness to be similar to those used in current turbine blade design.

For the present tests, all injected air was at ambient temperatures.

Injection system air is provided by an 71TD Ingersoll-Rand air compressor. The air is discharged from the compressor into three large storage tanks. As the schematic, Figure 2.2, shows the air flows from the storage tank through an adjustable regulator, a cut-off valve, moisture separator, flow regulator, a Fisher and Portor rotometer (full scale 9.345E-3 m/s, 19.8 SCFM, model 10A3565A). The rotometer which controls the volumetric flow rate, discharges the film coolant through a diffuser and into the injection heat exchanger and plenum chamber.

The heat exchanger and plenum chamber shown in Figure 2.3 is 0.305 x 0.508 x 0.457 m (23 x 20 x 18 in.) and is constructed of 1.27 cm (1/2 in.) plexiglass. Injection air flows over three metal plates 0.381 x 0.508 m (15 x 20 in.). The two lower plates are covered by silicon rubber heaters, 0.381 x 0.483 m (15 x 19 in.), rated at 120 volts. The heaters are controlled through a type 136 Powerstat variable autotransformer. The top surface of the chamber contains 13 plexiglass injection tubes each being 8 cm (3.15 in.) in length and with an inner diameter of 0.95 cm (3/8 in.). This corresponds to a length to diameter ratio of 8.42. The 13 injection holes discharge the coolant into the boundary layer at a 30 degree angle. There is a three-diameter spanwise spacing between the center of each hole.

Further discussion of the qualification and performance of the injection system can be found in [Ref. 10: p.23].

C. FIVE-HOLE PRESSURE PROBE

Multi-hole pressure probes are invaluable in the investigation and measurement of complex, three-dimensional flows. In particular, the five-hole probe is well suited for measurement of three mean velocity components in low speed incompressible flows.

The five-hole pressure probe used to measure pressure in this study is manufactured by United Sensors and Control Corp. (drawing number DA-125-24-F-22-CD). The probe shown in Figure 2.4 is 0.6096 m (2 ft.) in overall length with a probe diameter of 0.318 cm (0.125 in.). It is constructed of corrosion-resistant, non-magnetic stainless steel.

The five pressure holes are arranged in two different planes which intersect at the mutual hole, P_1. The probe tip is prismatic in geometry, as shown in Figure 2.4 The centrally located P_1 hole is normal to the freestream. The pitch plane consists of P_1, P_4, and P_5 pressure holes. While pressure holes P_1, P_2, P_3 constitute the yaw plane. The distance seperating P_2 and P_3 is 0.178 cm (0.070 in.), P_4 and P_5 are 0.155 cm (0.061 in.) apart. The central hole P_1 is 0.648 cm (0.255 in.) from the bottom of the probe tip. These distances were measured using a micrometer.

For calibration, the probe was positioned in a manual traversing unit manufactured by United Sensor and Control Corp., Figure 2.5. The unit was modified by the user to include a compass rose with a radius of 15.24 cm (6 in.) and a range of yaw angles from -40 to +40 degrees (0.25 degree accuracy). Additionally, the manual traversing unit positions the probe vertically in the mainstream 0 - 30.48 cm (0 - 12 in.) range. The manual traversing unit is mounted on top of a spanwise, horizontal sled. The sled is 62.23 cm (24.5 in.) wide and is designed to set in place on top of the wind tunnel's side walls. The spanwise mounting sled is designed such that the probe can be positioned 10.16 cm (4 in.) either side of centerline in increments of 0.635 cm (0.25 in.). In addition to spanwise positioning, the spanwise sled could be rotated through a range of pitch angles from -15 to + 15 degrees with an accuracy of 0.5 degrees.

After the completion of the probe calibration, an automated traversing mechanism, Figure 2.6, was used for probe positioning while measuring the pressures in the experimental test cases. The probe is fixed into the automated traversing mechanism in a position of zero yaw. The traversing mechanism has two degrees of movement which allows a thorough measurement of the flow field to be conducted. Both the spanwise and vertical traversing blocks are mounted on a 20-thread per inch drive screw and two ground steel, case-hardened steel guide support shafts. Each drive shaft is directly coupled to a SLO-SYN type MO92-FD310 stepping motor. The motors are controlled by a MITAS Two-Axis Motion Controller, Figure 2.7 The stepping motors and the controller are manufactured by Superior Electric Company. The controller directs the movement the probe in both the spanwise amd vertical directions. The MITAS controller comes equipped with 2K bytes of memory and an MC68000, 16-bit microprocessor which allows the user to program the start, stop, duration, speed, acceleration and deceleration of the stepping motors.

D. DATA ACQUISITION SYSTEM

The data acquisition system, shown in Figure 2.8 rapidly acquires the voltages associated with each pressure, converts each voltage to pressure.

1. Transducers and Demodulators

The probe is connected through reinforced plastic tubing to five Celesco model LCVR differential pressure transducers. These transducers have a designed pressure range of 0 -20 cm (0 - 7.85 in.) water and produce a 15 to 45 mV volt output signal. The transducer output signal is converted to a proportional DC signal by Celesco CD 10D carrier demodulators. Each demodulator has a maximum frequency response of -3dB at 500 Hz and a maximum out put noise of 10mV, peak to peak. Each transducer/carrier demodulator combination was calibrated against a Meridian 1.27 cm (0.5 in.) horizontal manometer with an accuracy of 0.002 cm (.005 in.) of water, to give typical calibration of approximately 1.0 volt per inch of water differential pressure.

2. Computers and Hardware

A Hewlett-Packard 85 microcomputer was used to acquire and process data for the calibration of the pressure probe. Configured with 64K bytes of memory and a single magnetic tape cartridge drive, the HP-85 was used to collect, store, display, and print the majority of the data required during the course of probe calibration.

For the measurement of the flow field, a Hewlett-Packard Series 300, Model 9836S computer was dedicated to the data acquisition process. The HP 9836S is equipped with a MC68000, 8 MHz 16/32-bit processor, Dual 5-1/4 inch floppy disk drives, and 1M bytes of memory. A HP 7470 two pen plotter was used for the graphic representation of data.

Each transducer carrier demodulator combination is connected directly to a HP 3498A extender which is controlled by a HP-3497A data acquisition control unit. The HP-3497A which provides precision measurement and process monitoring, is equipped with analog multiplexing and a digital voltmeter with 1μV sensitivity.

Six software programs were developed for use during the thesis. PROCAL was developed for use with the HP-85 and was used during the probe calibration phase. PRSACQ, VEL, VELC, PLOT, VECTOR were developed for use with the HP 9836S. PRSACQ is used to measure the pressures in the various flow fields. VEL and VELC are used to compute the velocity components. PLOT and VECTOR are used for the plotting of results. A thorough discussion of the programs requires an understanding of the calibration procedures and the velocity measurement techniques as discussed in Chapter Three.

III. CALIBRATION AND MEASUREMENT PROCEDURES

Prior to using the five-hole pressure probe to measure flow velocities, it is necessary to calibrate the probe to determine the dependence of yaw, pitch, static, and total coefficients on yaw and pitch angles.

A. COORDINATE SYSTEM

A right hand coordinate system, Figure 3.1 was established for use throughout the course of study. The X-axis is parallel to the streamwise direction and is positive in the downstream direction. The Y-axis is in the vertical plane and is positive from the wind tunnel's bottom wall. The Z-axis is in the vertical plane and is positive from the wind tunnel's bottom wall. The Z-axis is in the spanwise direction. The origin of the coordinate system is located on the centerline line of the bottom wall.

Yaw, β, is defined as rotation about the Y-axis and was arbitrarily defined as positive when the direction of the flow resulted in pressure P_3 being greater than P_2. This condition corresponds to positive component of velocity in Z direction. The pitch angle, α, is defined as rotation about the Z-axis and is defined as positive when P_4 is greater than P_5.This condition results in a positive component of velocity in the Y direction.

B. EXPERIMENTAL PROCEDURES

The five-hole pressure probe was calibrated using the method described by Treaster and Yocum, [Ref. 12].

To perform the calibration, the probe is placed in the manual traversing unit which is mounted on top of the spanwise horizontal sled as described in Chapter Two. The probe is normal to the freestream when P_2 is equal to P_3 which gives β equal to zero.

The probe was manually fixed at a predetermined yaw angle and then rotated through the pitch plane. At each point, the data acquisition system records the five pressures. Four pressure coefficients are then calculated by the PROCAL program.

Calibration of the probe was conducted over a range of yaw angles from -20 degrees to +20 degrees in four-degree increments. The pitch angle was varied from -15 degrees to +15 degrees in five-degree increments. This provided a cone of angles which was sufficient for the flows to be studied in this thesis. Calibration was performed in the NPS Shear Layer Tunnel at a freestream velocity of approximately 21 m/s (68.89 ft/sec). The probe was located 1.6 m (5.3ft) from the boundary layer trip. This equates to a Reynolds number of 1.97×10^6 based on downstream distance. Static pressure was obtained from a static pressure tap on the tunnel side wall and total pressure from a Kiel probe inserted into the flow through the top wall. Static and total pressures are measured once per set of calibration points. Atmospheric pressure is used as the reference pressure.

C. CALIBRATION COEFFICIENTS

To use the probe for measurement of complex flows, it is necessary to determine the flow angles, α and β, and the local static and total pressures. This can be done by determining four non-dimensional pressure coefficients over a range of angles in both the yaw and pitch planes. The four calibration coefficients are defined as:

$$Cp_{yaw} = (P_2 - P_3)/(P_1 - \bar{P}) \qquad \text{(eqn 3.1)}$$

$$Cp_{pitch} = (P_4 - P_5)/(P_1 - \bar{P}) \qquad \text{(eqn 3.2)}$$

$$Cp_{total} = (P_1 - P_{total})/(P_1 - \bar{P}) \qquad \text{(eqn 3.3)}$$

$$Cp_{static} = (\bar{P} - P_{static})/(P_1 - \bar{P}) \qquad \text{(eqn 3.4)}$$

where

$$\bar{P} = (P_2 + P_3 + P_4 + P_5)/4 \qquad \text{(eqn 3.5)}$$

To be of value in measuring a flow field, the calibration coefficients must be a function of flow angle only, independent of velocity and repeatable. Figure 3.2 shows that the calibration is both independent of velocity and repeatable in the yaw plane.

As previously stated, probe calibration was conducted by fixing the yaw angle and varying the pitch angle. Theoretically, a calibration procedure of fixing the pitch angle and rotating through the yaw angles should provide identical results. However, in this study when the fixed pitch vary yaw method was attempted, the results were not identical. The trend of Cp_{pitch} vs. pitch angle showed significant scatter, and Cp_{total} vs. pitch angle was not constant for each yaw angle.

D. RESULTS

Figure 3.3 shows the variation of Cp_{yaw} with the yaw angles for various pitch angles. The response is nearly linear for all yaw angles. The results show that values of Cp_{yaw} for various pitch angles collapse on top of each other for yaw angles of -12 degrees to +8 degrees. This means that Cp_{yaw} is independent of pitch angle in this range. From -23 degrees to -15 degrees and from +8 degrees to +15 degrees, there are slight variations in the results indicating that Cp_{yaw} has a slight dependency on the pitch angle. The fact that yaw is only slightly dependent on the pitch angle allows data to be more easily processed in determination of flow velocity.

The variation of Cp_{pitch} vs. pitch angle, Figures 3.4 and 3.5, show that this coefficient is dependent on both yaw and pitch angles. The trend of Cp_{pitch} vs. pitch angle is generally linear but there are variations from that linearity for each yaw angle, and unlike the yaw plane, these variations are not restricted to any particular region.

Figures 3.4 and 3.5 show that the range of values for Cp_{pitch} is small over the range of α shown compared to the variation of Cp_{yaw} with β. [Ref. 12: pp. 27-28] attribtues this to the types of surfaces on which the holes in the pitch and yaw plane are connected. Large yaw angles result in one hole being nearly aligned with the flow. This hole senses a pressure nearly equal to the total pressure of the freestream. The other hole is then blocked from the freestream and, consequently, reads a pressure much less than the freestream static pressure. The holes in the pitch plane have a different response to variation in the pitch angle. When pitched, one hole reads a pressure which is near the total pressure of the freestream, but the second hole senses a pressure which is greater than the freestream static pressure. Thus, Cp_{yaw} is a much larger number than Cp_{pitch}. The small range of Cp_{pitch} increases the scatter and uncertainty of pitch angle measurements.

The plot of Cp_{static} vs. pitch angle, Figure 3.6, shows that Cp_{static} has weak dependency on yaw and pitch angles.

Cp_{total} vs. pitch angle, Figure 3.7, indicates that for any given yaw angle, Cp_{total} is constant throughout the range of pitch angles. Here, Cp_{total} also shows a weak dependency on yaw and pitch angles.

E. INTERPOLATION AND APPLICATION

After the probe has been calibrated and the operating characteristics of the probe are known, it is possible to determine the pitch angle, yaw angle, local static and total pressures for any flow field,

The probe is positioned normal to the freestream, and at any location in the flow field, the five pressures can be measured. These five pressures are now used to calculate the experimental or local coefficients of yaw, pitch, static pressure, and total pressure.

A fifth order polynomial was fitted to the average values of Cp_{yaw}. The resulting polynomial computed using a FORTRAN program based on the least-squares method is:

$$\beta_{app} = -.158 - 7.36(M_1) + 0.135(M_1)^2 + 0.304(M_1)^3 + 0.009(M_1)^4 - 0.031(M_1)^5 \qquad \text{(eqn 3.5)}$$

Here, β_{app} is the approximate yaw angle, and M_1 is the local coefficient of yaw.

Knowing the approximate yaw angle and the local Cp_{pitch}, a computerized interpolation is performed to determine the pitch angle. Since the value of the pitch angle is dependent on the local Cp_{pitch} and on the yaw angle, it is necessary to perform a double interpolation. Referring to Figure 3.8, the two yaw angles, β_1 and β_2, which bracket the approximate yaw angle are first determined. Next, the local Cp_{pitch}, M_{2a} and M_{2b}, is located between known values of Cp_{pitch} from the calibration data for each yaw angle. In Figure 3.8, these values are designated C_{11}, C_{12}, C_{21}, and C_{22} which correspond to pitch angles from the calibration data of α_{11}, α_{12}, α_{21}, and α_{22}. The bracketing pitch angle α_{1f} is determined by the following interpolation

$$(C_{11} - M_{2a})\,(C_{11} - C_{12}) = (\alpha_{11} - \alpha_{1f})\,(\alpha_{11} - \alpha_{12}) \qquad \text{(eqn 3.6)}$$

which rearranged gives

$$\alpha_{1f} = \alpha_{11} - (\alpha_{11} - \alpha_{12})((C_{11} - M_{2a})\,((C_{11} - C_{12})) \qquad \text{(eqn 3.7)}$$

The other bracketing pitch angle α_{2f} is found in a similar manner which gives

$$\alpha_{2f} = \alpha_{21} - (\alpha_{21} - \alpha_{22})((C_{21} - M_{2b})/(C_{21} - C_{22})) \quad \text{(eqn 3.8)}$$

The pitch angle for the flow α_f is found through a second interpolation which results in the relationship

$$\alpha_f = \alpha_{1f} - (\alpha_{1f} - \alpha_{2f})((\beta_1 - \beta_{app})/(\beta_1 - \beta_2)) \quad \text{(eqn 3.9)}$$

Because Cp_{yaw} has a slight dependency on pitch, it is necessary to refine the approximate yaw angle once the local pitch angle is known. This is done with a computerized interpolation routine which is very similar to that used for the pitch angle. As shown in Figure 3.9, the pitch angles from the calibration data, α_1 and α_2, which bracket the local pitch angle, α_f are first determined. The local Cp_{yaw}, M_{1b}, is then located between the values of Cp_{yaw} from the calibration data for α_1 This results in C_{31} and C_{21} which correspond to yaw angles β_{11} and β_{12}. Then, by linear interpolation β_{1f} is found

$$(C_{31} - M_{1b})/(C_{31} - C_{21}) = (((\beta_{11} - \beta_{1f})/(\beta_{11} - \beta_{12})) \quad \text{(eqn 3.10)}$$

or

$$\beta_{1f} = \beta_{11} - (\beta_{11} - \beta_{12})((C_{31} - M_{1b})/(C_{31} - C_{21})) \quad \text{(eqn 3.11)}$$

The same interpolation is done for α_2 which gives

$$\beta_{2f} = \beta_{21} - (\beta_{21} - \beta_{22})((C_{32} - M_{1a})/(C_{32} - C_{22})) \quad \text{(eqn 3.12)}$$

β_{2f} and β_{2f} are the yaw angles which bracket the yaw angle of the flow. The flows yaw angle, β_f, can be found by a second interpolation which results in the relationship

$$\beta_f = \beta_{2f} - (\beta_{2f} - \beta_{1f})((\alpha_2 - \alpha_f)/(\alpha_2 - \alpha_1)) \quad \text{(eqn 3.13)}$$

Since local total and static pressures are not measured at each probe location, it is necessary to perform another double interpolation to compute their values. From the calibration data, the values of Cp_{total} for each of the bracketing yaw angles and pitch angles are known. In Figure 3.10, these points are designated C_{11}, C_{12}, C_{21}, and C_{22}. An interpolation is performed to determine the Cp_{total} corresponding to the local pitch angle. These points are designated, C_{1f} and C_{2f}. The local Cp_{total}, M_3, is found using the relationship

$$(C_{1f} - M_3)/(C_{1f} - C_{2f}) = (\beta_1 - \beta_f)/(\beta_1 - \beta_2) \qquad \text{(eqn 3.14)}$$

which when rearranged as shown below gives the local Cp_{total} for the flow

$$M_3 = C_{1f} - (C_{1f} - C_{2f})((\beta_1 - \beta_f)/(\beta_1 - \beta_2)) \qquad \text{(eqn 3.15)}$$

The local Cp_{static}, M_4 is found in a similar manner. Referring to Figure 3.11, the relationship for determining the local Cp_{static} is then given by

$$M_4 = C_{3f} - (C_{3f} - C_{4f})((\beta_1 - \beta_f)/(\beta_1 - \beta_2)) \qquad \text{(eqn 3.16)}$$

F. VELOCITY COMPONENT DETERMINATION

Once the values of the local Cp_{total} and Cp_{static} have been determined, the local total and static pressure can be calculated and, subsequently, the total velocity at the probe tip can be determined.

The defining relationships for Cp_{total} and Cp_{static} can be rearranged to determine P_{total} and P_{static}:

$$P_{total} = P_1 - (Cp_{total})(P_1 - \bar{P}) \qquad \text{(eqn 3.17)}$$

$$P_{static} = \bar{P} - (Cp_{static})(P_1 - \bar{P}) \qquad \text{(eqn 3.18)}$$

By using Bernoulli's equation, the magnitude of the local total velocity is:

$$V = \sqrt{2(P_{total} - P_{static})/\rho} \qquad \text{(eqn 3.19)}$$

The three components of velocity can now be determined using the total velocity vector and the local pitch and yaw angles. Referring to Figure 3.1, these velocity components are given by,

$$V_x = V\cos\alpha\cos\beta \qquad \text{(eqn 3.20)}$$

$$V_y = V\sin\alpha \qquad \text{(eqn 3.21)}$$

$$V_z = V\cos\alpha\sin\beta \qquad \text{(eqn 3.22)}$$

G. SPATIAL RESOLUTION CORRELATION

The calculation of V_y may be influenced by the local total velocity gradient. Corrections for this effect may be made using the following relationship

$$V_{yf} = V_{yo} + (\partial U/\partial x)(ly) \qquad \text{(eqn 3.23)}$$

Here V_{yo} is the uncorrected value of V_y and V_{yf} is the value of V_y corrected for spatial resolution. The value of ly used was slightly greater than the distance between P_4 and P_5 (0.155 cm): a value of 0.200 cm gave constant V_y through the two-dimensional boundary layer.

H. SOFTWARE

Six programs were developed for use during this study. They are PROCAL, PRSACQ, VEL VELC, PLOT, and VECTOR. Each program is written in BASIC. PROCAL was used with the HP-85, all others were written for the HP-9836S. All of the programs are listed in Appendix C.

PROCAL is a BASIC program used for the calibration of the pressure probe. The program begins by computing the correction factor for random noise associated with each transducer. The user is then prompted to manually calibrate each transducer against a horizontal monometer. Static pressures are input utilizing a static pressure tap on the side wall and one of the transducers. Total pressure of the freestream is input using a Keil probe inserted into freestream and a transducer. The user is next prompted to input the ambient pressure in inches of mercury. After the user has positioned the probe at the desired angles of yaw and pitch, those angles are input into the program.

The computer then acquires the five voltages from the data acquisition system, converts each voltage to a pressure in inches of water, and then calculates the yaw, pitch, total, and static coefficients of pressure. Finally, the yaw angle, pitch angle, and the four coefficients are stored on a separate file and printed out utilzing the HP-85's internal printer.

PRSACQ was used to acquire the pressures during the experiment. PRSACQ begins by prompting the user for the number spanwise and vertical data points and the resolution. A matrix of data point location is then computed. Next, the transducers are corrected for noise and calibrated against the manometer. Freestream static and total pressures are measured and ambient conditions are input. The program enters a loop which samples each pressure ten times per probe location. The local Cp_{yaw} and Cp_{pitch} are computed. Probe position, Cp_{yaw}, and Cp_{pitch}, P_1 and P_{total} are stored in a matrix. At the end of the data collection run, these values are read into a data file on a floppy disk.

VEL is used to process the raw data acquired by PRSACQ. The data is first read into computer memory. The program computes an approximate Cp_{yaw} using a polynomial fit. Next, double interpolation subroutine is used to comput local Cp_{pitch}. A second interpolation subroutine is used to refine the value of Cp_{yaw}. The values of the Cp_{pitch} and Cp_{yaw} are used in a third interpolation subroutine to compute the local Cp_{static} and Cp_{total}. The total pressure is found from the definition of Cp_{total}. The velocity at the probe tip is computed, and the x, y, and z components of velocity are determined. Probe position (y and z coordinates), total pressure, total velocity, and V_x, V_y, and V_z are stored in a matrix and then read into a data file.

VELC corrects the V_y component for spatial resolution. PLOT is used to generate graphs of streamwise velocity, total velocity, and total pressure. VECTOR is used to plot the secondary flow vectors.

IV. EXPERIMENTAL RESULTS

The study was conducted in three parts. The first was the measurement of baseline data consisting of boundary layer profiles in a two-dimensional mean flow field. The second was the measurement of the boundary layer characteristics at a freestream velocity of 15 m/s with 1) film cooling only, 2) with embedded vortex only, and 3) with both film cooling and embedded vortex. The third part was the measurement of boundary layer with vortex at 20 m/s, and measurement of boundary layer with vortex and film cooling at a freestream velocity of 11 m/s.

A. BASELINE RESULTS

The baseline boundary layer profiles were conducted at a freestream velocity of 22 m/s. For these tests, the top wall of the wind tunnel was adjusted at 20 m/s freestream velocity so that a zero pressure gradient existed within 0.15 mm water along the length of the test section. Profiles were taken at three spanwise locations $z = +2.54$ cm, $z=0$ cm, and $z=-2.54$ cm. Figure 4.1 shows measurements of the streamwise velocity, V_x. Figure 4.2 shows measurements of V_z. Figures 4.3 and 4.4 show mesurements of the normal velocity, V_y. The results of the baseline measurements indicate behavior expected of a 2-D turbulent boundary layer, since the figures show mean profiles to be spanwise uniform for all three velocity components. Figures 4.2 and 4.3 show that the V_z and the corrected V_y components are small and nearly zero as would be expected. Figure 4.4 is the plot of V_y uncorrected for spatial resolution.

B. 15M/S FREESTREAM VELOCITY RESULTS

The investigation of the flow field was conducted by using the five-hole pressure probe to measure pressures at 800 points in a spanwise plane. Data was taken at 20 different vertical locations, each having 40 spanwise locations. All 15 m/s measurements were taken at a location of 1.49 meters from the boundary layer trip or 0.39 meters from the heat transfer plate leading edge. The film cooling cases were conducted with injection air at 75% of full scale on the rotometer which corresponds to a blowing ratio (ratio of coolant to mass fluxes) of 0.50.

1. **Boundary layer with film cooling**

The results of boundary layer with film cooling only and no vortex are shown in Figures 4.5 to 4.8. Figure 4.5 shows contours of the streamwise velocity, Figure 4.6 shows total velocity contours, Figure 4.7 is the plot for total pressure, and Figure 4.8 shows the secondary flow vectors. Away from the wall, outside the boundary layer, the first three figures show spatially uniform behavior for V_X, V, and P_O. Secondary flow vectors are very small everywhere in Figure 4.8. Near the wall deficits of V_X, V, and P_O correspond to locations of the film cooling jets which are located about every 3.0 cm from tunnel centerline.

2. **Boundary layer with vortex**

The vortex is generated by using a half-delta wing which is 3.0 cm high with 7.5 cm chordand an angle of 18°. It is identical to vortex generator # 2 described by Joseph, [Ref. 10: p.76]. The vortex generator was located at a spanwise location of z=4.79 cm (note that the direction of +z in [Ref. 10: p.75] is reversed). Figure 4.9 shows the streamwise velocity results, Figure 4.10 is a plot of the total velocity contours, Figure 4.11 is a contour plot of total pressure, and Figure 4.12 shows the secondary flow vectors. The contour plots for V_X,V, and P_O show significant deficits caused by the generator wake which is rolled up with the vortex. The center of the wake is located at y=3.3 cm and z=-3.05 cm. Figure 4.12 shows that the vortex center is located near the same location, with overall characteristics similar to a Rankine vortex. Figure 4.13 shows the streamwise vorticity contours, where the vorticity is calculated using

$$\omega_f = (\partial V_z/\partial y) - (\partial V_y/\partial z) \quad \text{(eqn 4.1)}$$

The vorticity is largest near the vortex center as expected. The circulation of the vortex is estimated to be 0.2708 m^2/s using the equation

$$\Gamma = \int \omega_X dA. \quad \text{(eqn 4.2)}$$

3. **Boundary layer with vortex and film cooling**

Figure 4.14 shows the streamwise velocity contours for this case, Figure 4.15 is the total velocity contour plots, Figure 4.16 shows the results for total pressure. Figure 4.17 shows the secondary flow vectors, and Figure 4.18 is a contour plot of vorticity. Figure 4.15, 4-16, and 4-17 show that the deficits for V_x, V, and P_0 from the film cooling are no longer present near the vortex. This result shows that the effects of film cooling are decimated by the vortex. The effect of the vortex is particularly pronounced near its downwash side. As for the previous case, Figure 4.18 shows that vorticity is again highest near the vortex center. Figure 4.19 from [Ref. 10: p.99] shows that the results of this case are consistent with previous work by Joseph which shows high heat transfer rates on the downwash side of the vortex and low heat transfer rates on the upwash side of the vortex. The circulation for this case is estimated to be 0.2708 m^2/s.

C. 20 M/S AND 10 M/S FREESTREAM VELOCITY RESULTS

Figure 4.20 is a plot of streamwise velocity for the case of an embedded vortex with no film cooling with a freestream velocity of 20 m/s. Figure 4.21 is a plot of the secondary flow vectors for the same case. Figure 4.22 and Figure 4.23 are for a boundary layer with embedded vortex and film cooling at 11 m/s freestream velocity. The blowing ratio for the 20 m/s case is 0.38, and the blowing ratio at 11 m/s was 0.68. The results for both cases show trends which are similar to those discussed above. The results at a freestream velocity of 11 m/s are believed to be less reliable because of disturbances at the inlet of the tunnel which propagated to the test section during the time period the data was acquired.

V. SUMMARY AND CONCLUSIONS

Measurements are presented of boundary layers with embedded vortices and with film cooling for freestream velocities of 15, and 11 m/s. Measurements of a boundary layer with embedded vortex and and no film cooling, and of a boundary layer with film cooling but no vortex are presented for freestream velocity of 15 m/s. Plots of total velocity, V, streamwise velocity, V_x, secondary flow vectors, total pressure. P_0, and streamwise vorticity are presented for many of these test conditions.

The results show that the embedded vortices completely dominate the flow field in boundary layers with film cooling. This is indicated from the plots of V, V_x, and P_0 which show the effects of film cooling to be completely decimated in the vicinity of the vortex. This result is consistent with the heat tranfer results of Joseph, [Ref. 10: p.54], which shows a localized hot spot at the wall near the same location. Future film cooling injection-hole arrangements in turbine blades must be designed to compensate for hot spots due to the vortices.

In order to conduct this study, a five-hole pressure probe was calibrated for pitch and yaw. The probe was then used to measure five pressures associated with the flow. From these pressures, total velocity and the x, y, and z components of velocity were determined.

A boundary layer profile was conducted to verify the calibration of the pressure probe, measurement procedures, and velocity computations. The results show expected boundary layer behavior with a small V_y and V_z component.

It is recommended that flow visulization study of the interaction between the vortex and film cooling be conducted to enhance the understanding of this complex phenomena.

APPENDIX A
FIGURES

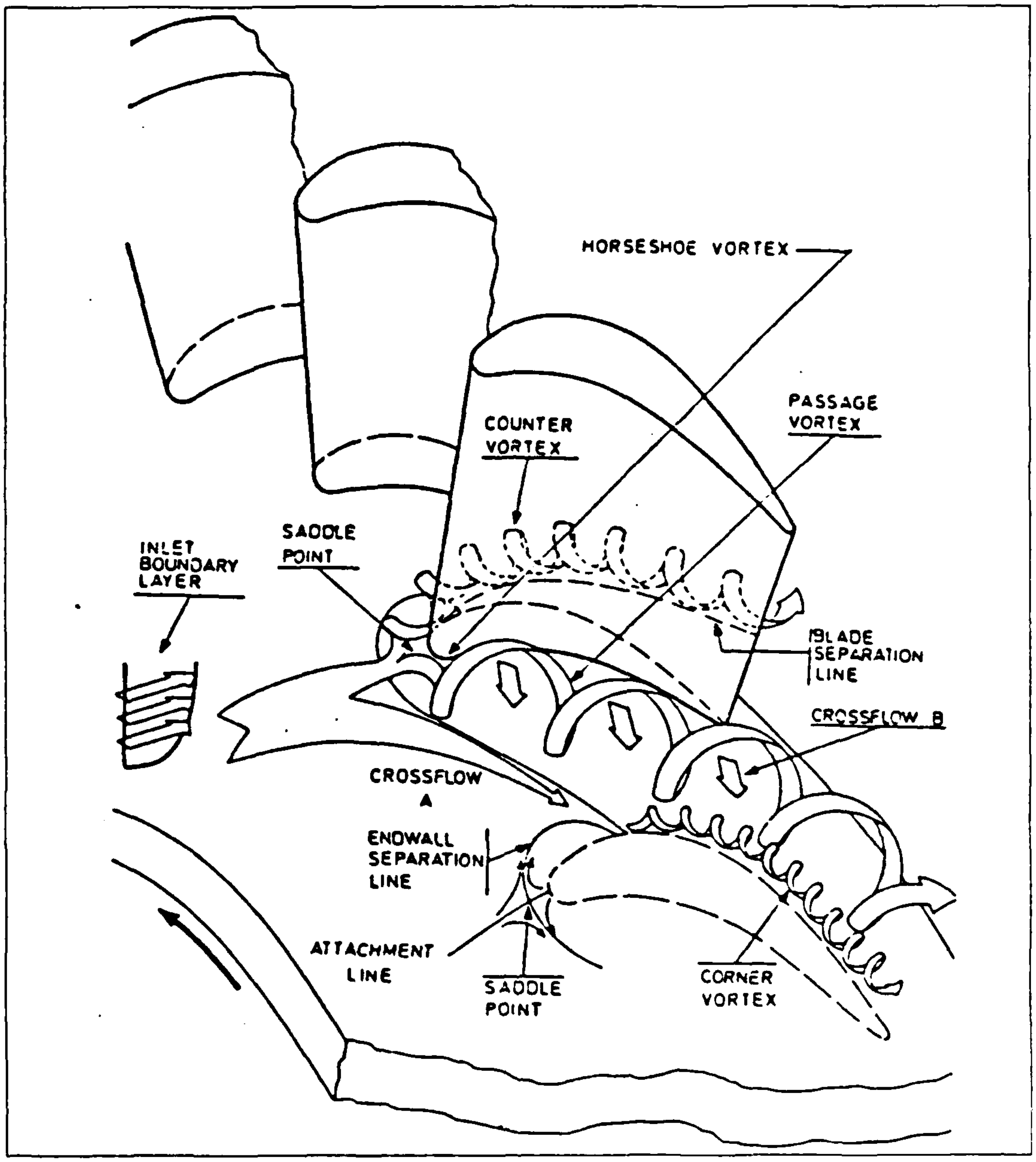


Figure 1.1 Endwall secondary flows.

1. Saddle point
2. Separation line of inlet end wall boundary layer
3a. End wall separation line of suction side leg of leading edge vortex
3b. End wall separation line of "pressure side leg of leading edge vortex" and or passage vortex
4. Start of suction side end wall corner vortex
5. Low energy region

Figure 1.2 Smoke and oil visulization for rotor blade.

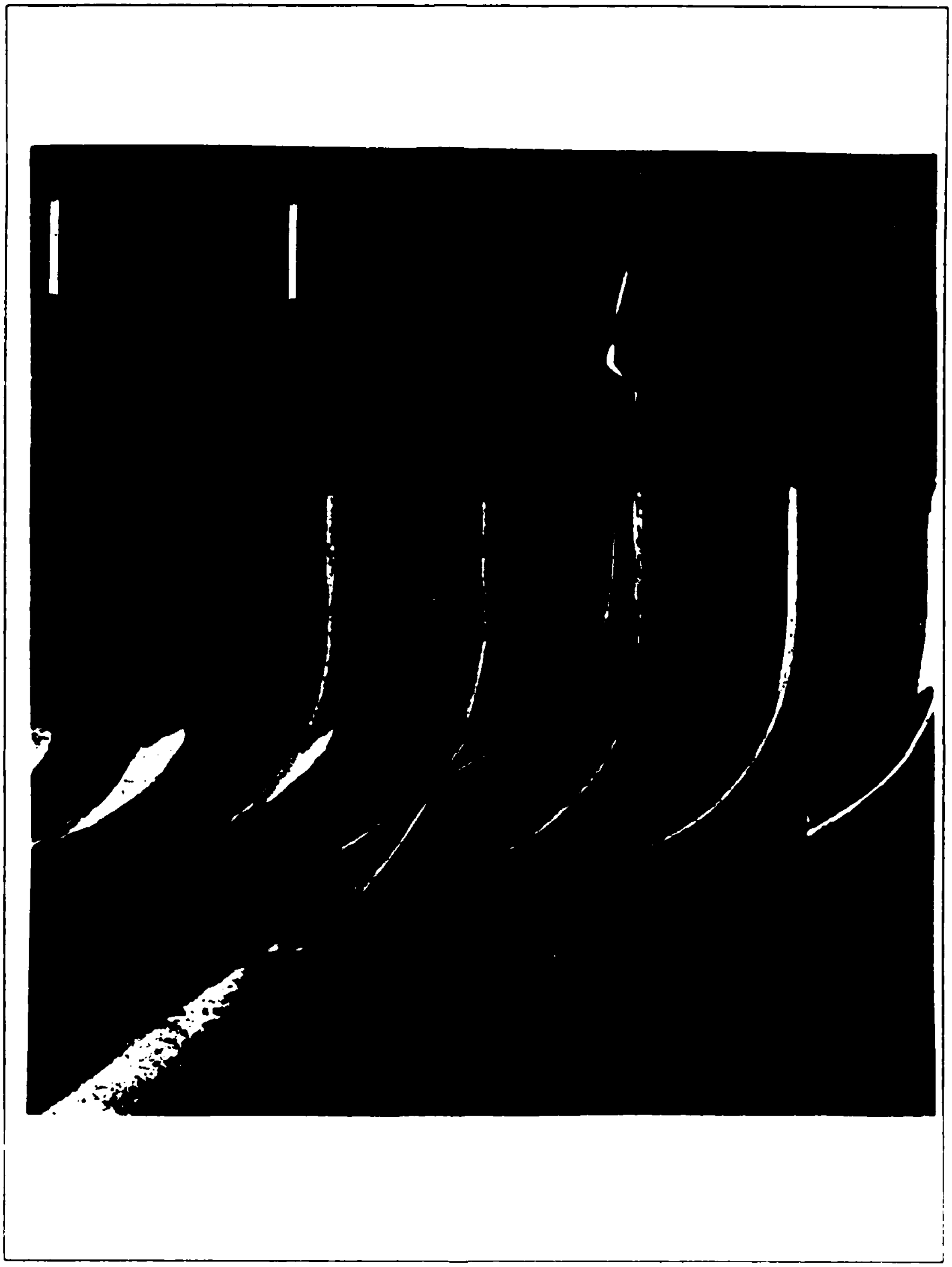


Figure 1.3 Secondary flow deflection.

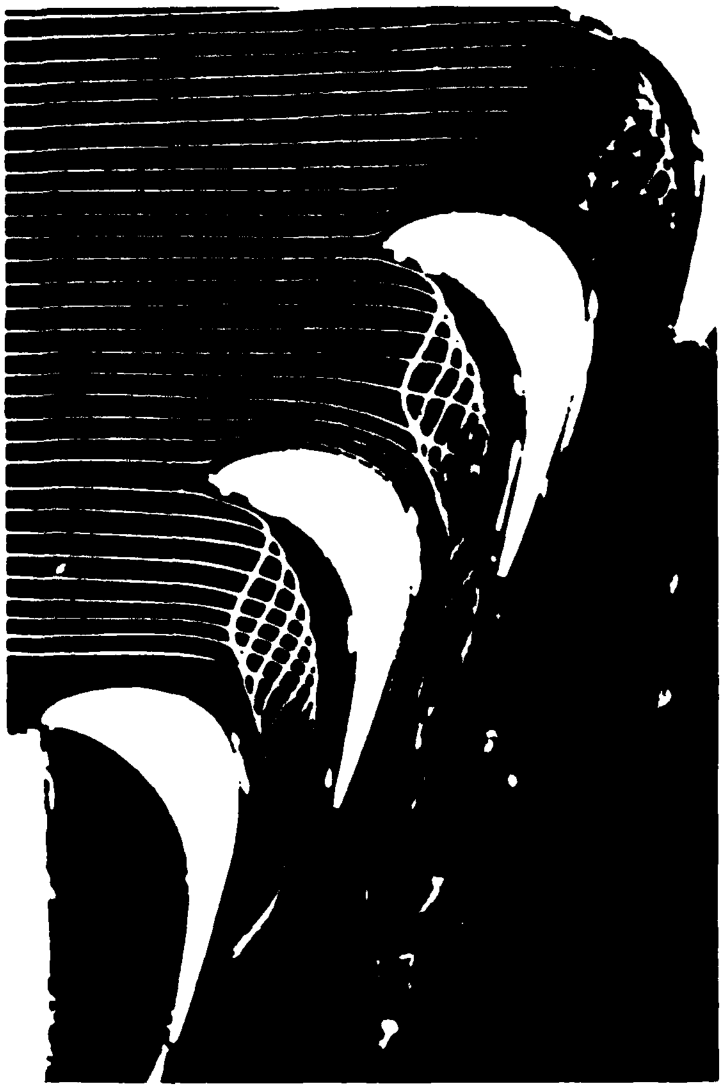


Figure 1.4 Rotation of passage and corner vortices in turbine cascade.

Figure 2.1   Photographs of wind tunnel

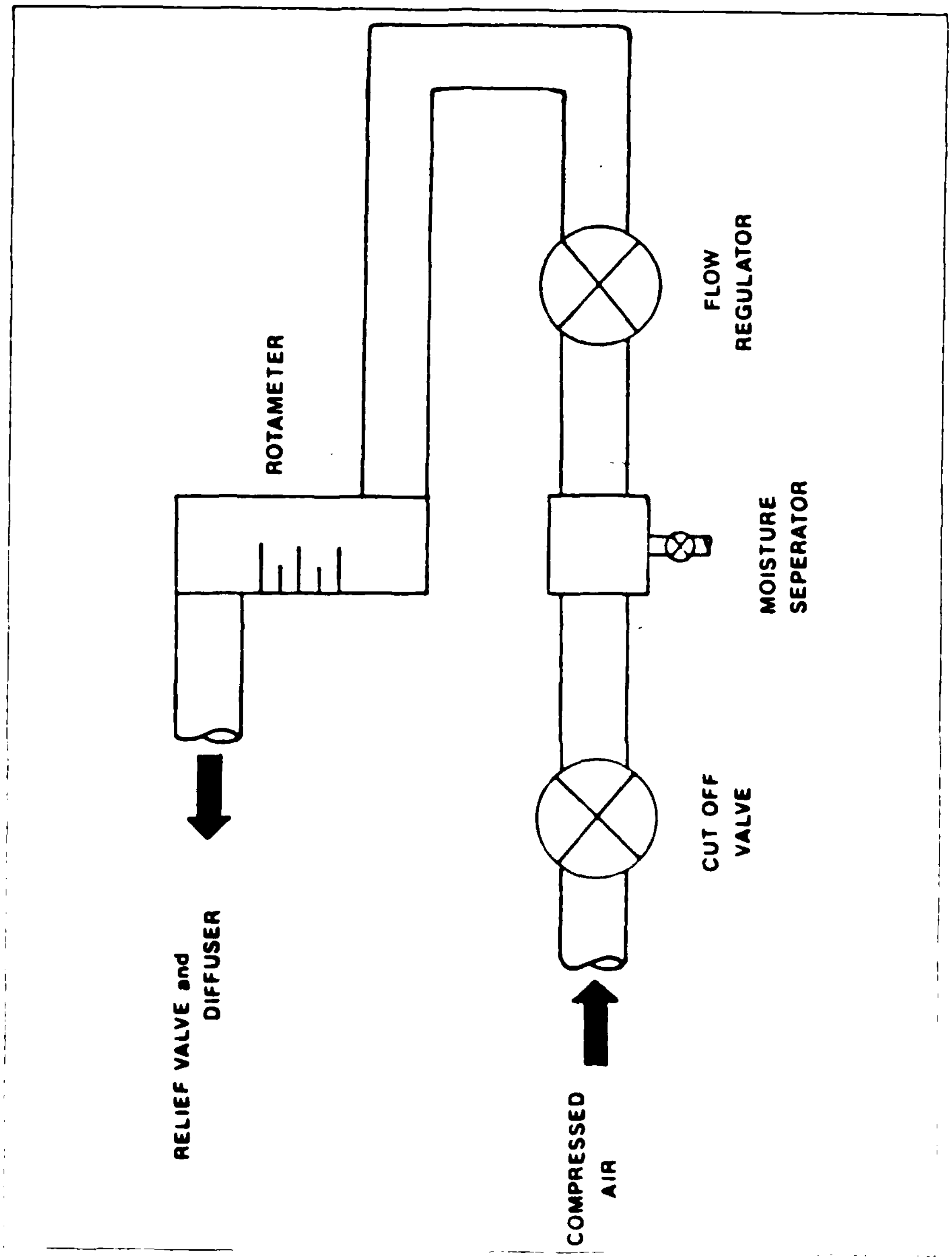


Figure 2.2 Schematic of injection air flow

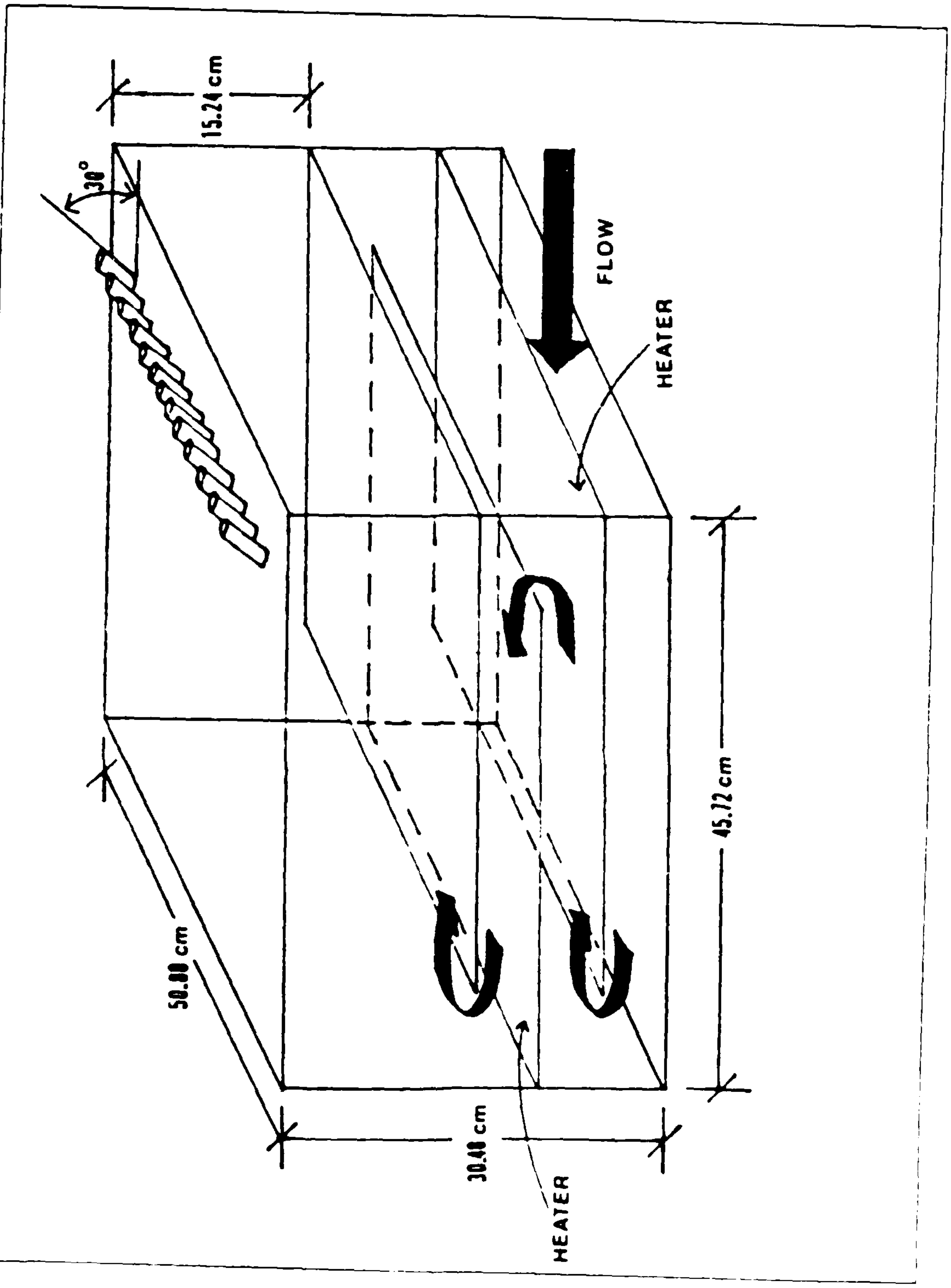


Figure 2.3 Schematic of injection plenum.

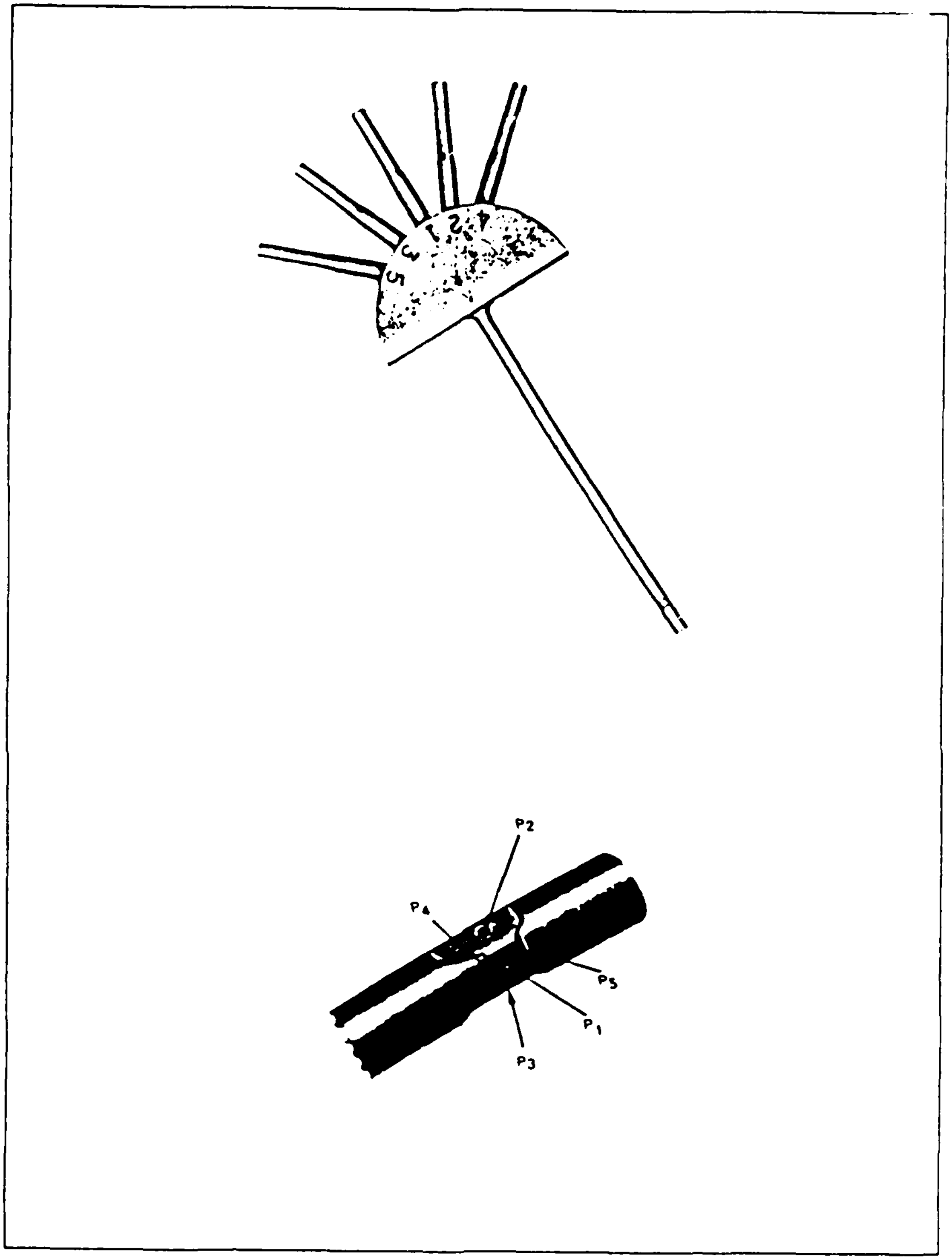


Figure 2.4 Photographs of pressure probe.

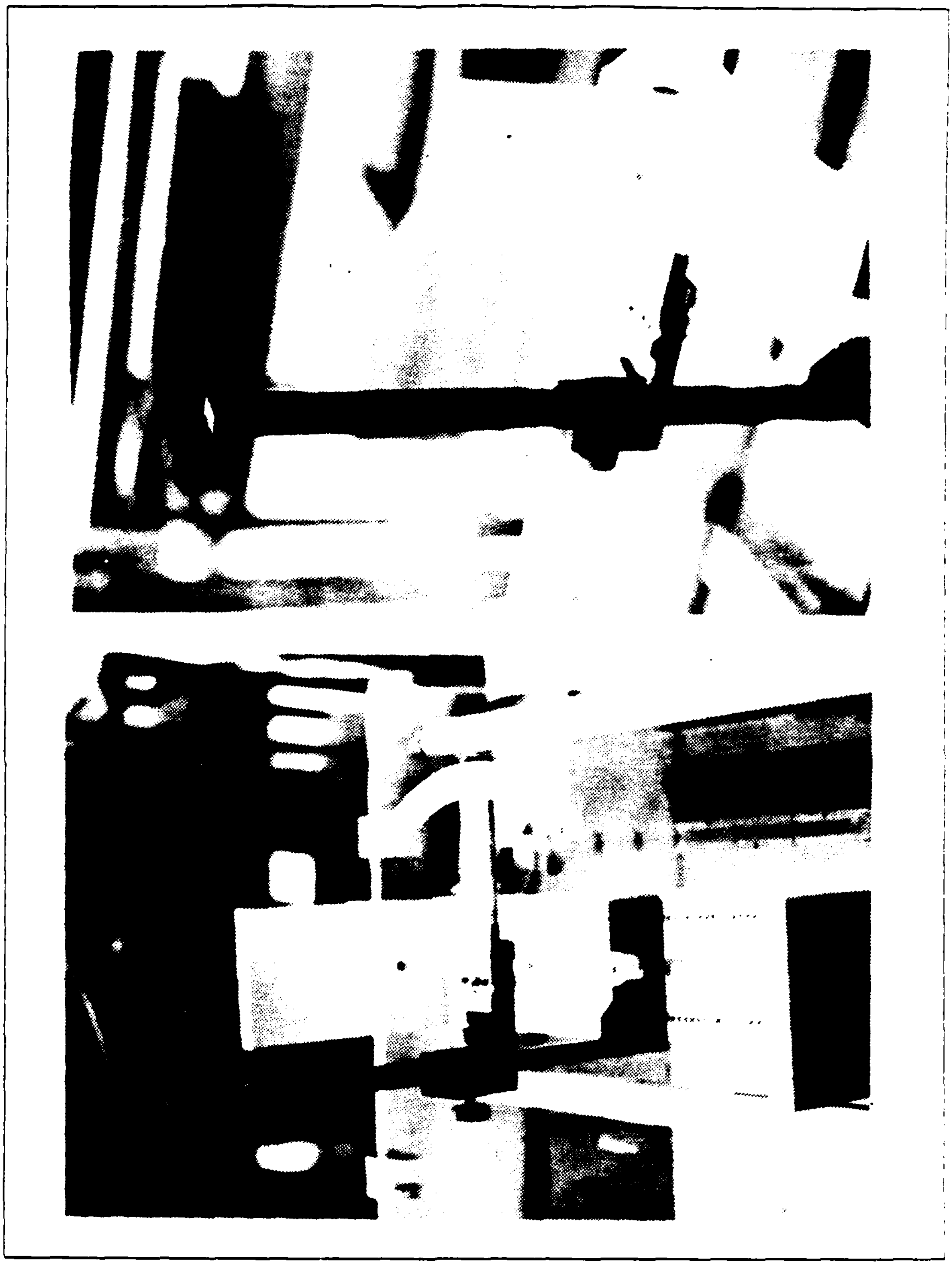


Figure 2.5 Manual traversing device.

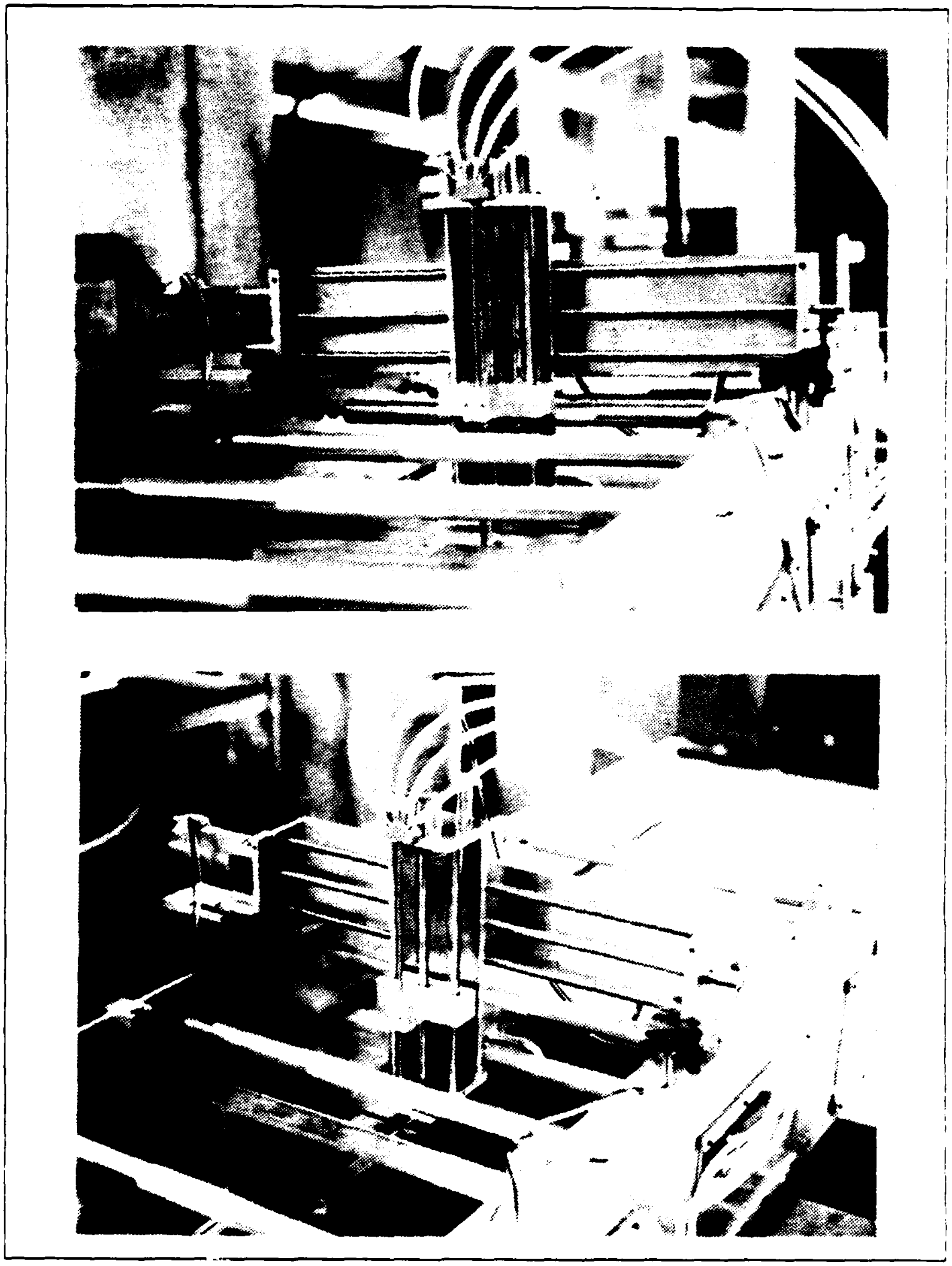


Figure 2.6 Automated traversing mechanism.

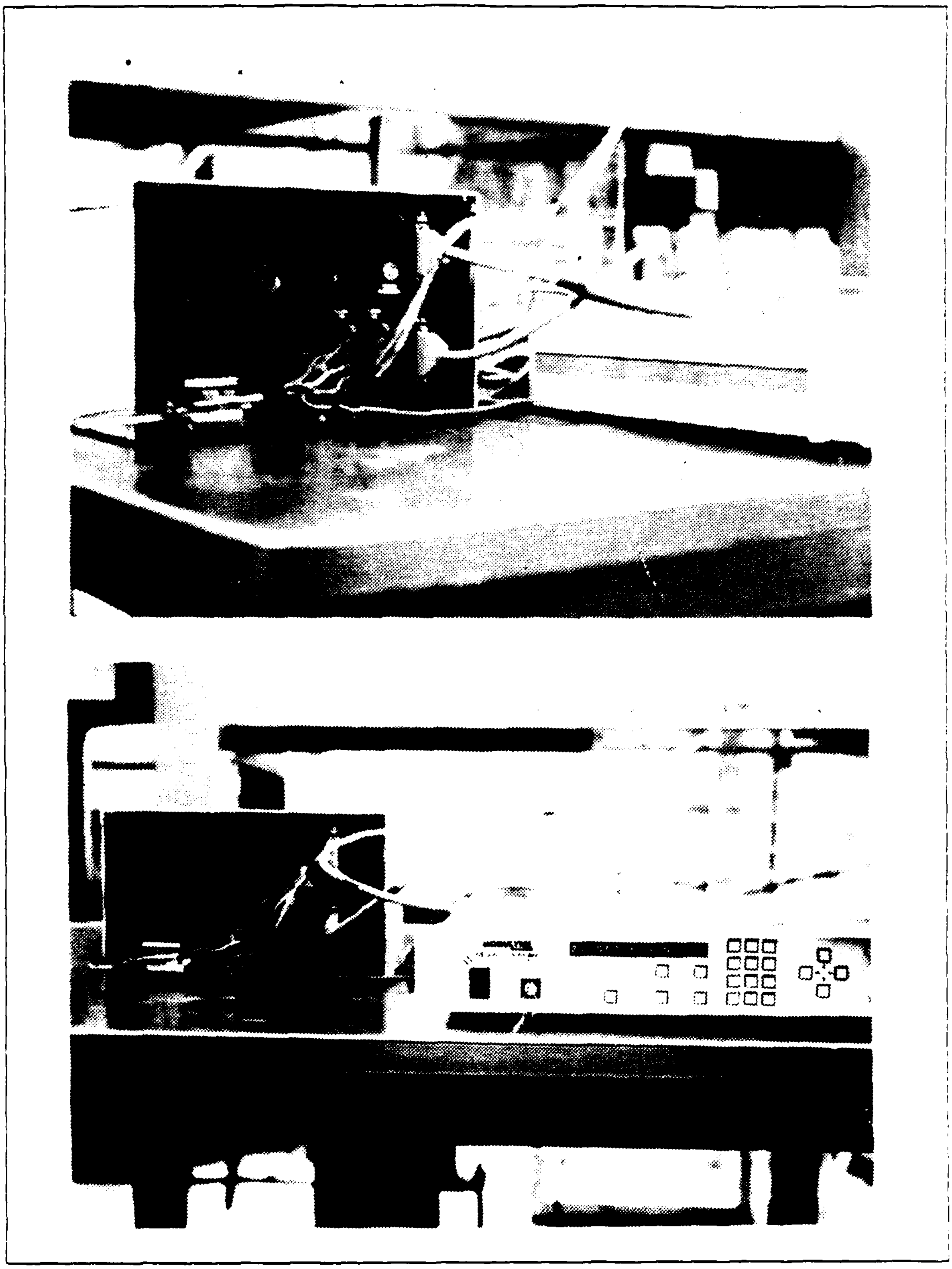


Figure 2.7 Photographs of Two-Axis Motion Controller.

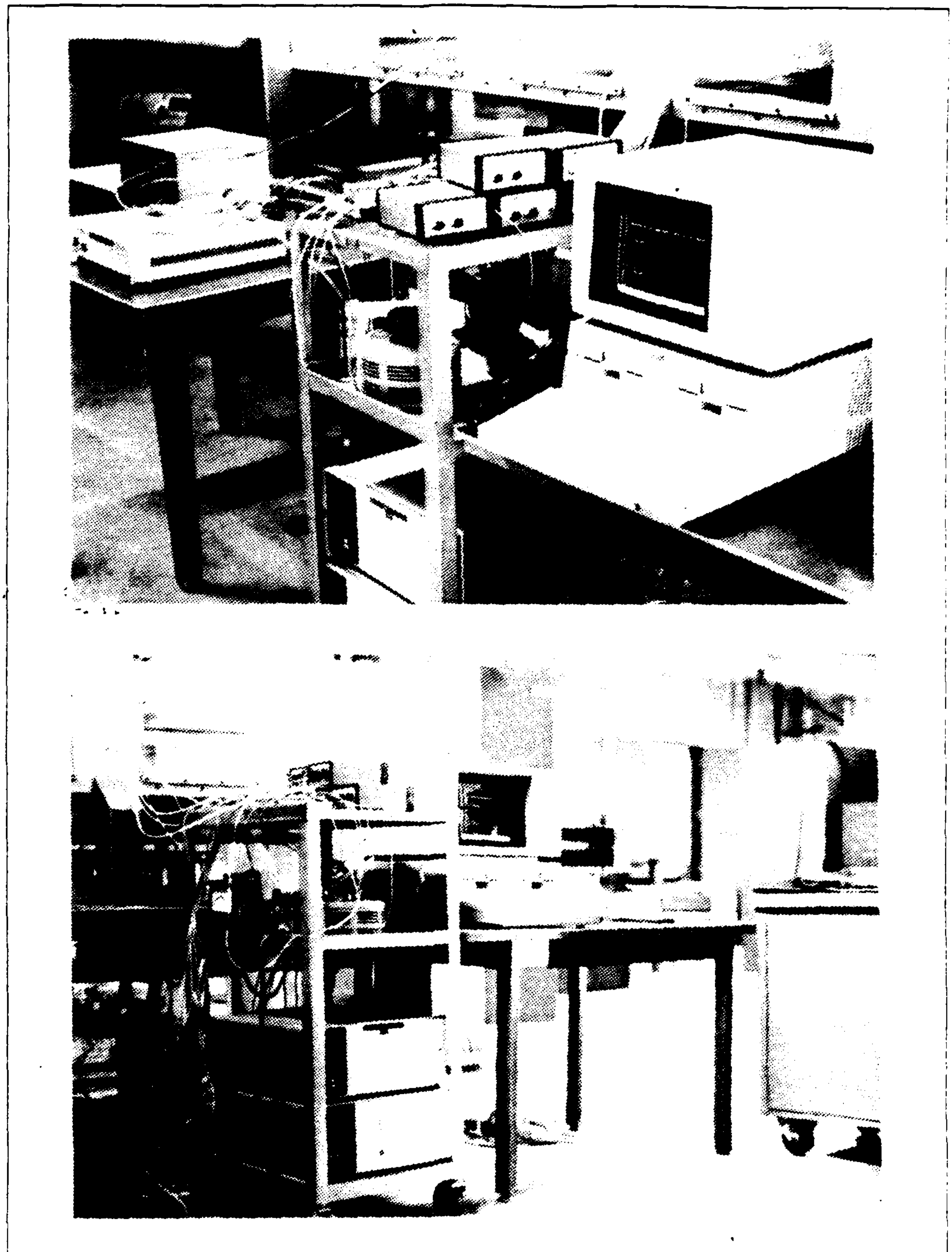


Figure 2.8 Photographs of data acquistion system.

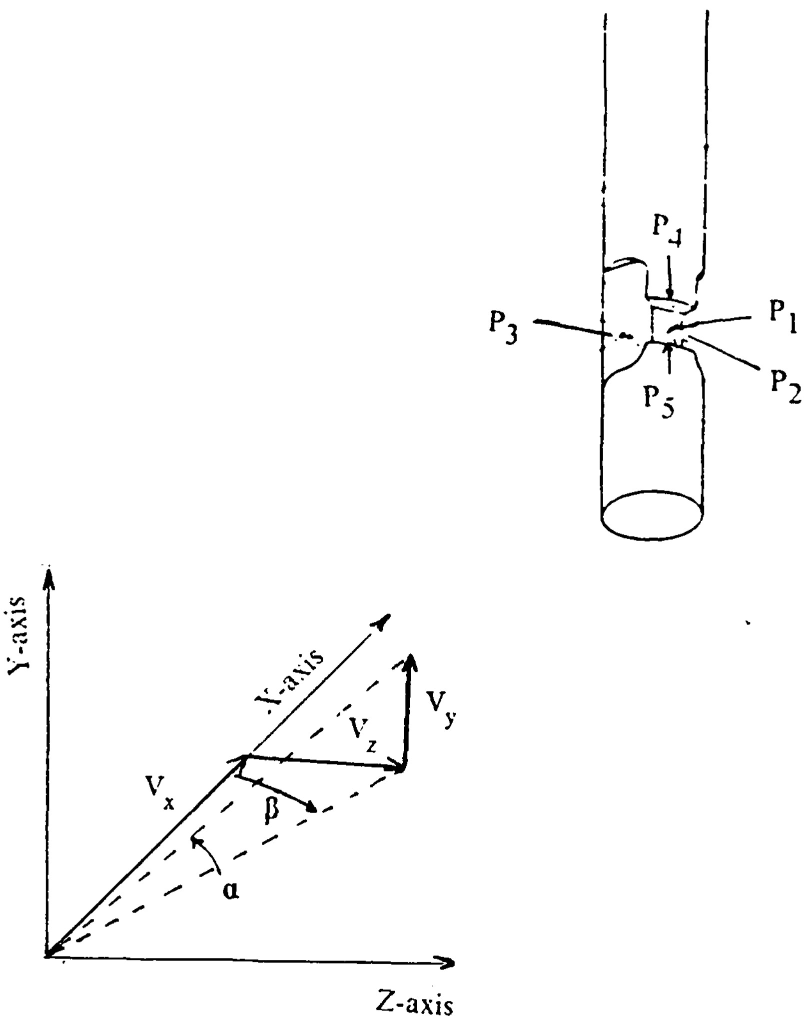


Figure 3.1 Coordinate system for flow measurement.

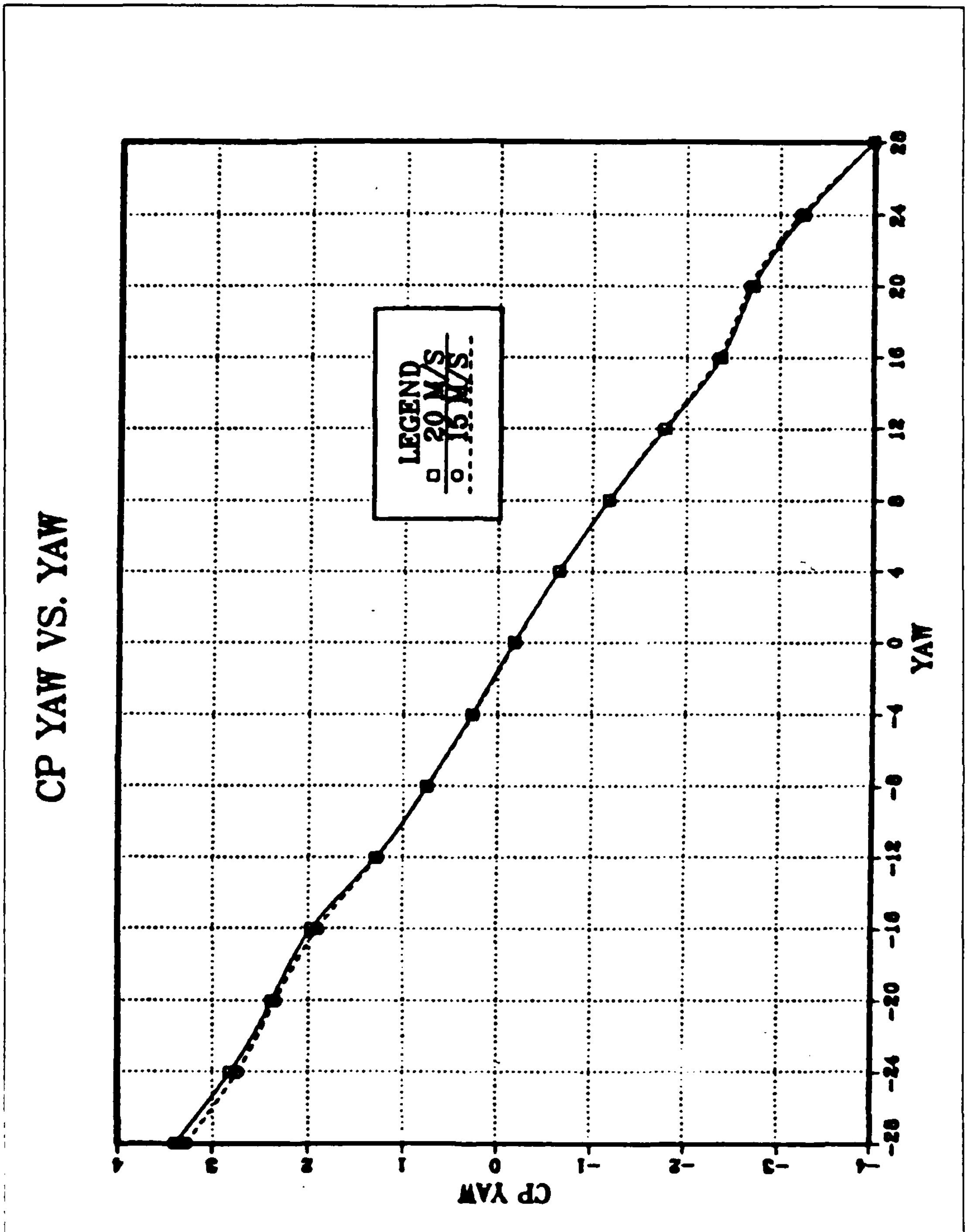


Figure 3.2 Repeatability of calibration results at different freestream velocities for Cp_{yaw} vs. yaw angles.

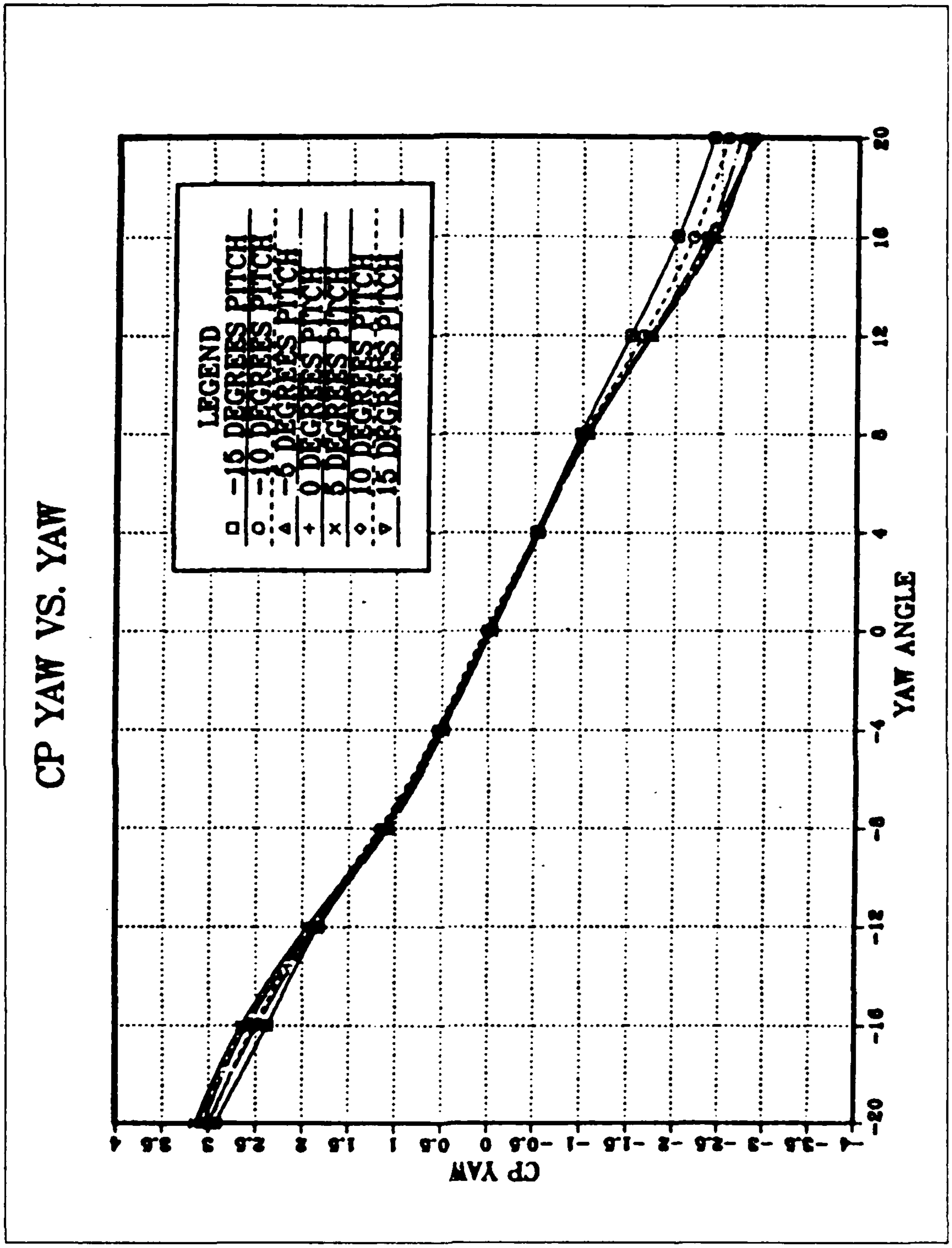


Figure 3.3 Probe calibration, Cp_{yaw} vs. yaw angles, freestream velocity of 21 m/s.

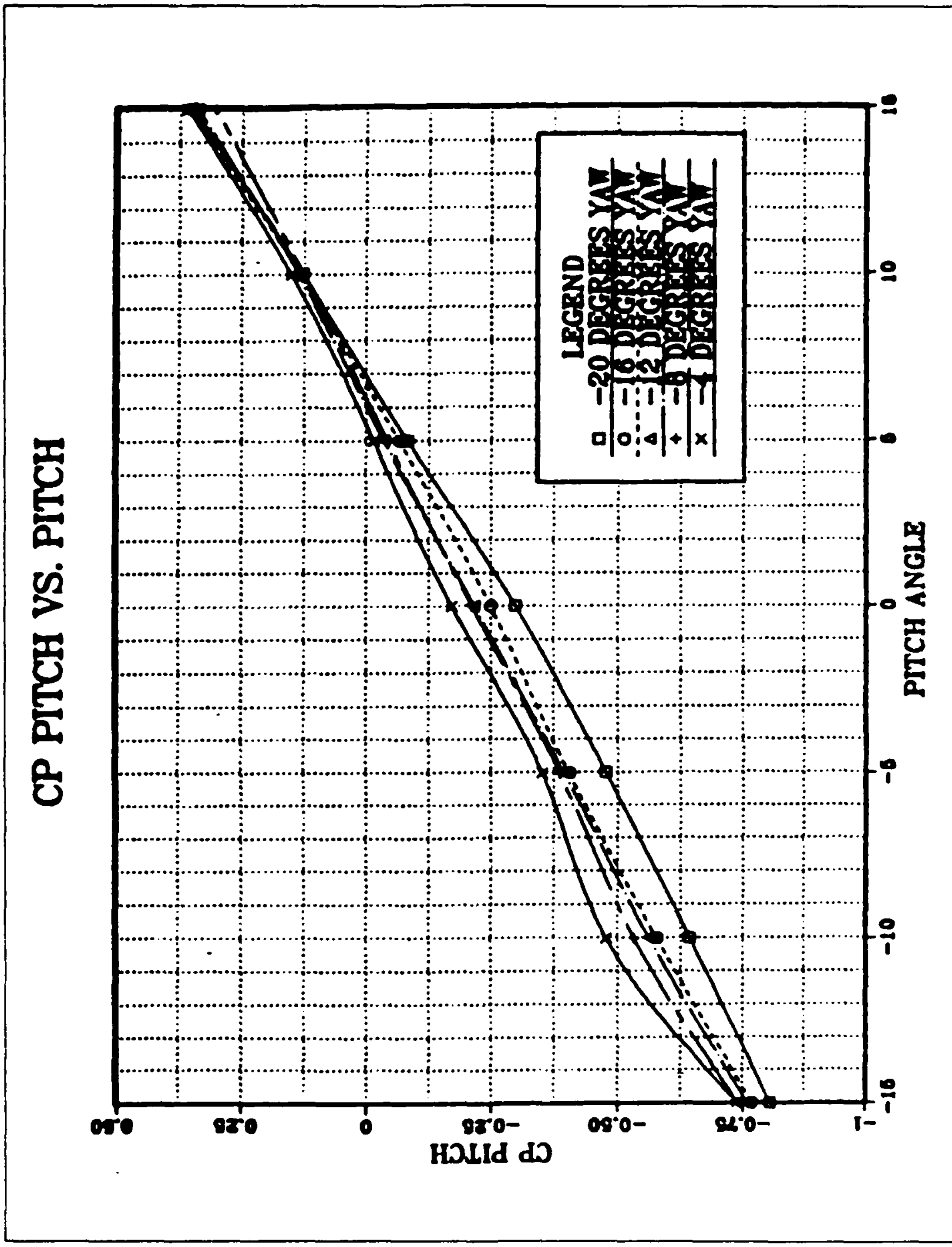


Figure 3.4 Probe calibration, Cp_{pitch} vs. pitch angle for -20° to -4° yaw, freestream velocity of 21 m/s.

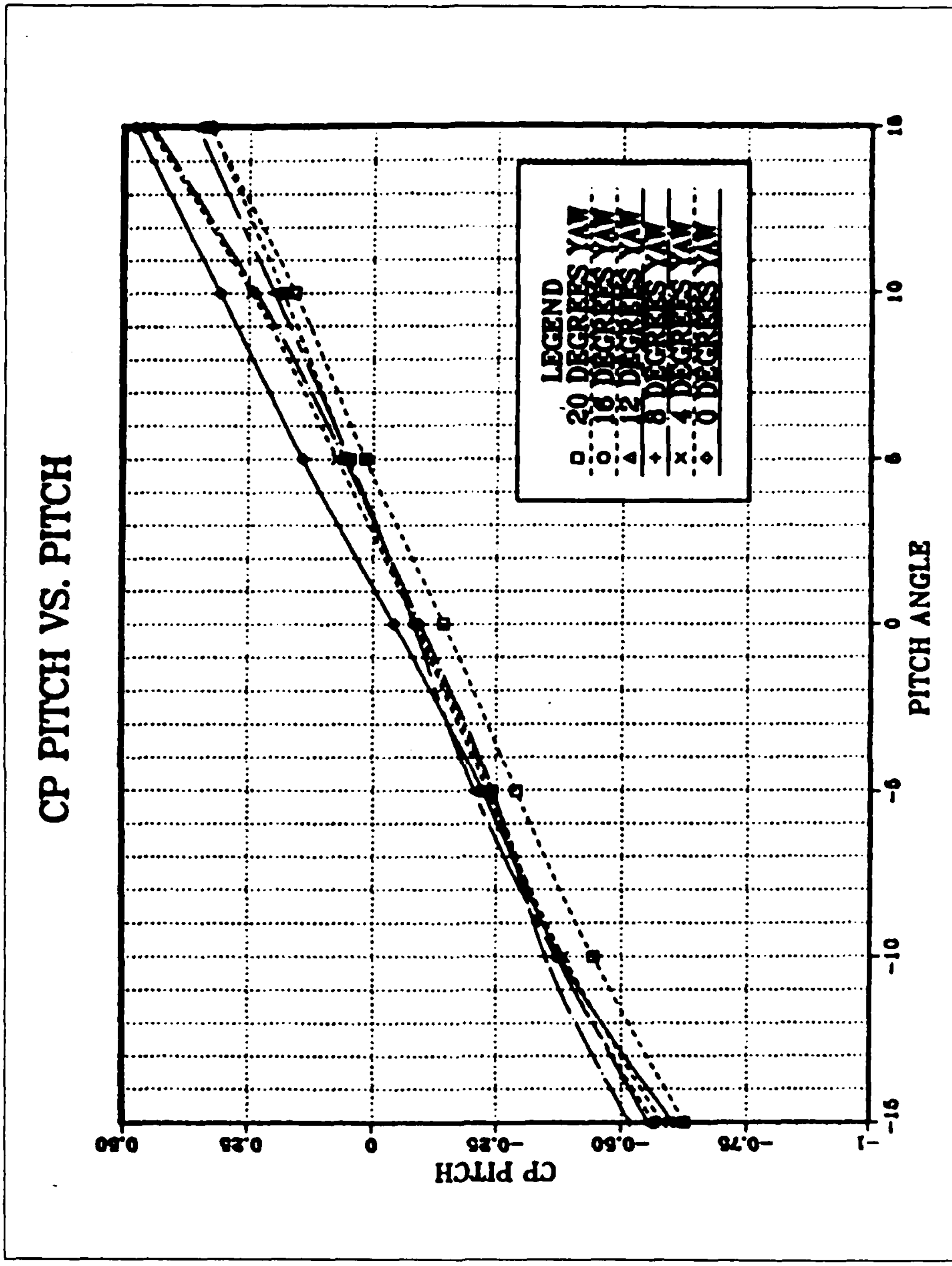


Figure 3.5 Probe calibration, Cp_{pitch} vs. pitch anglefor 0° to +20° yaw, freestream velocity of 21 m/s.

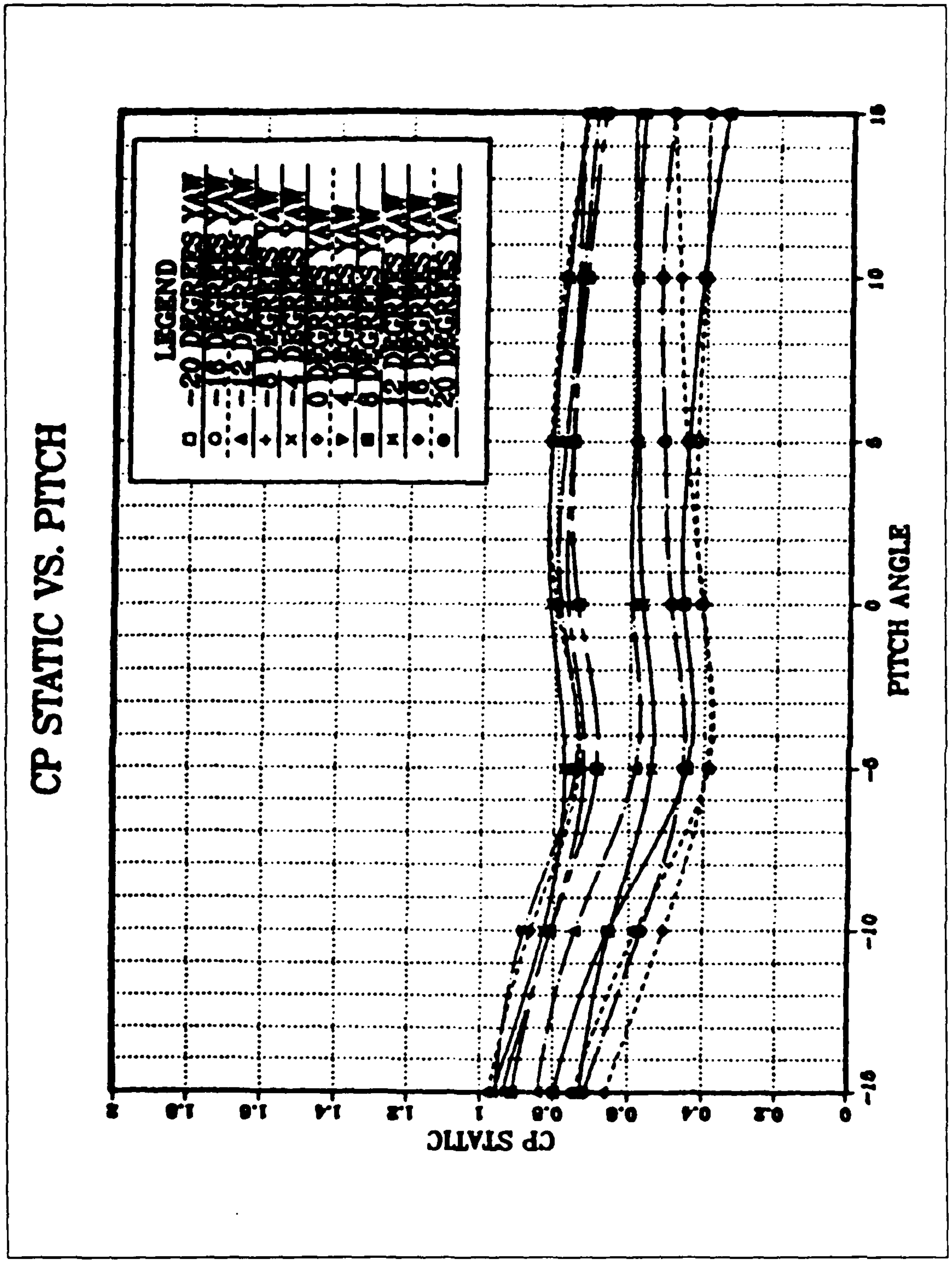


Figure 3.6 Probe calibration, Cp_{static} vs. pitch angles, freestream velocity of 21 m/s.

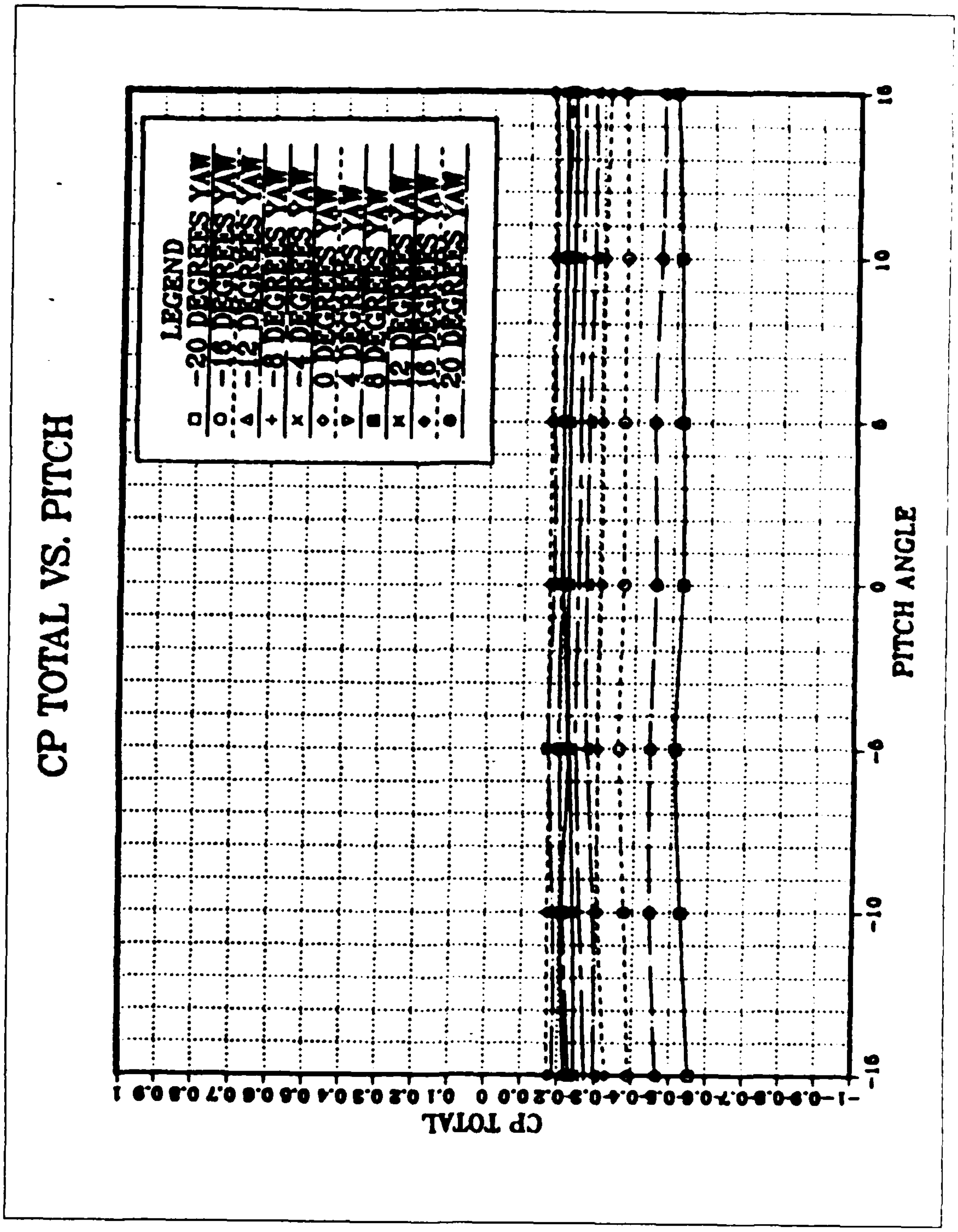


Figure 3.7 Probe calibration, Cp_{total} vs. pitch angles, freestream velocity of 21 m/s.

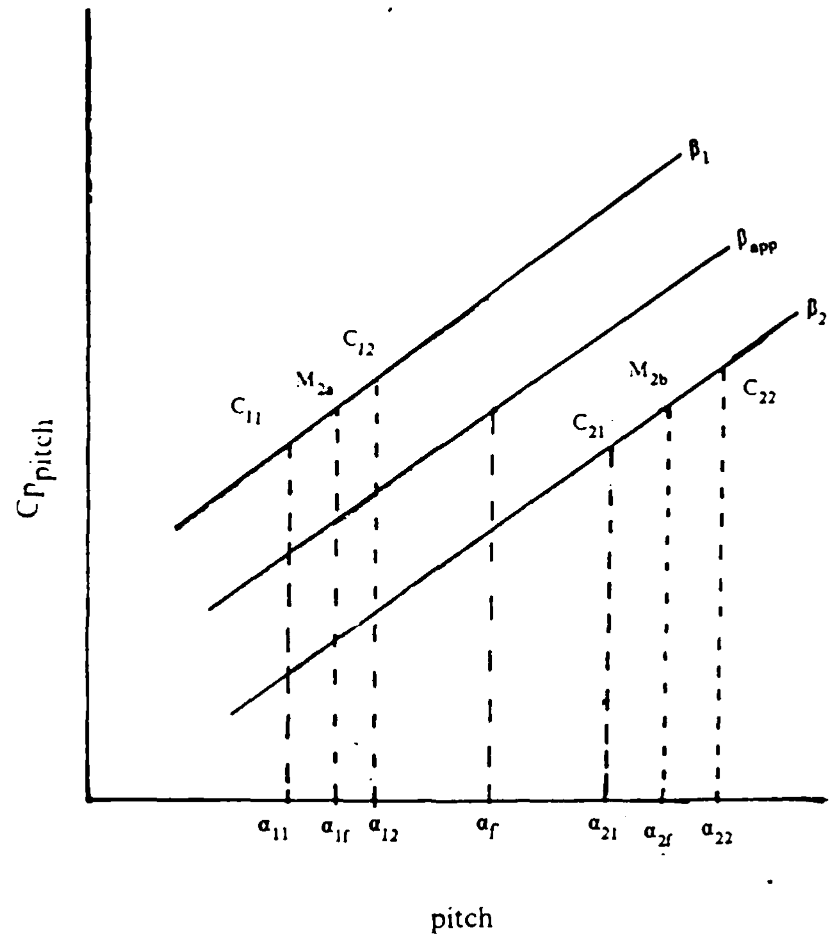


Figure 3.8 Interpolation for pitch angles.

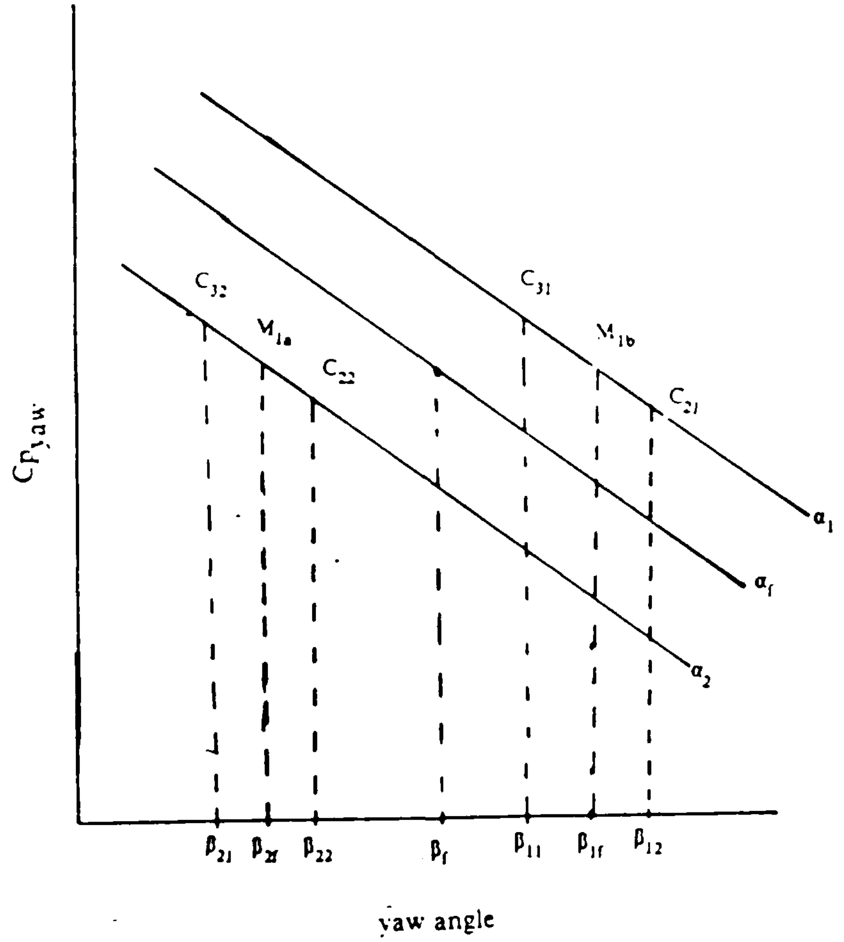


Figure 3.9 Interpolation for yaw angles.

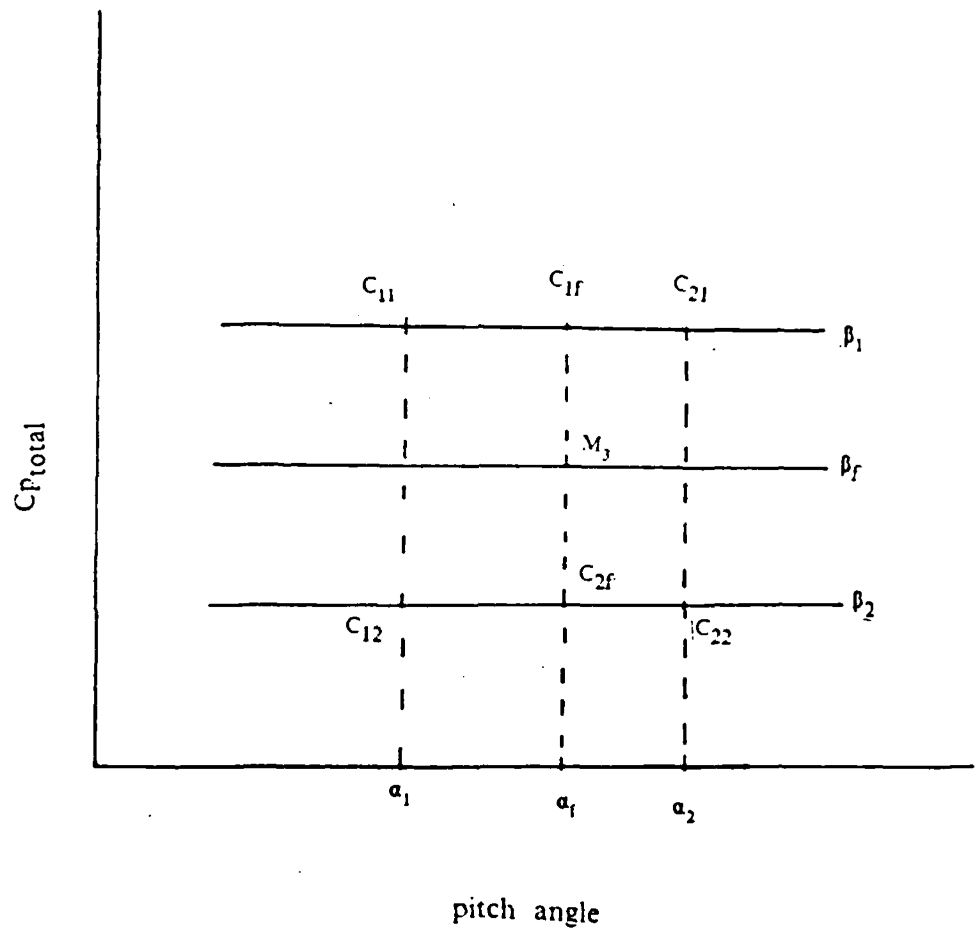


Figure 3.10 Interpolation for local Cp_{total}.

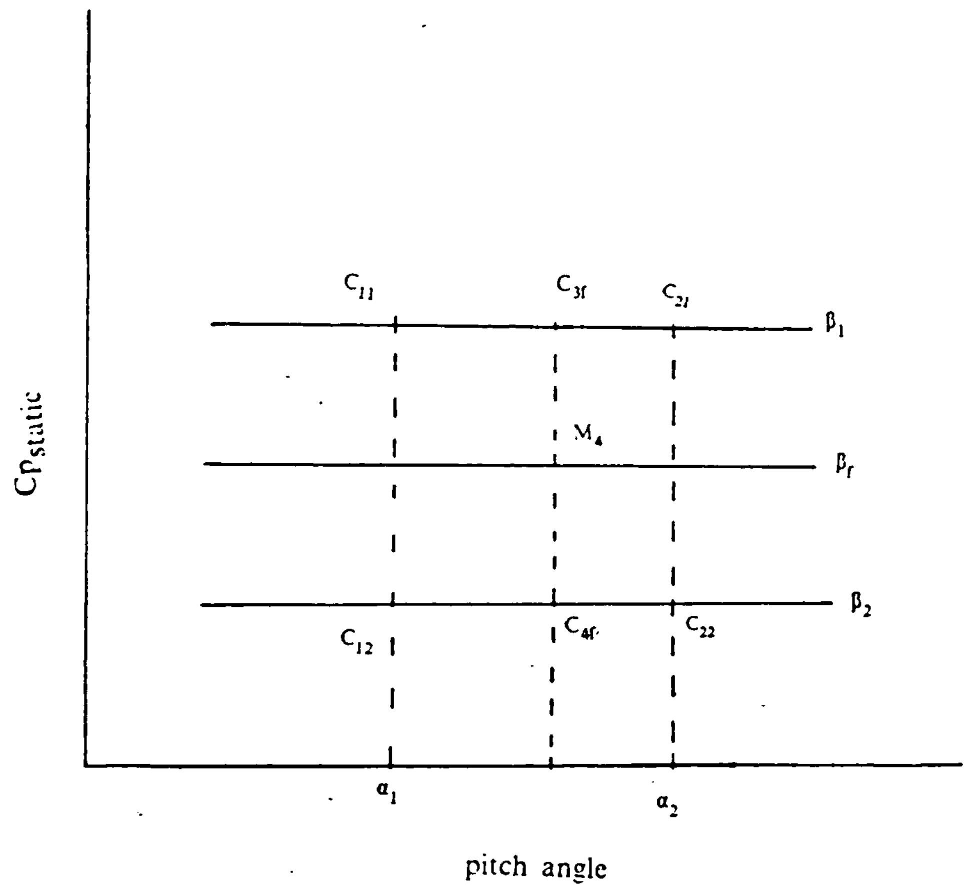


Figure 3.11 Interpolation for local Cp$_{static}$

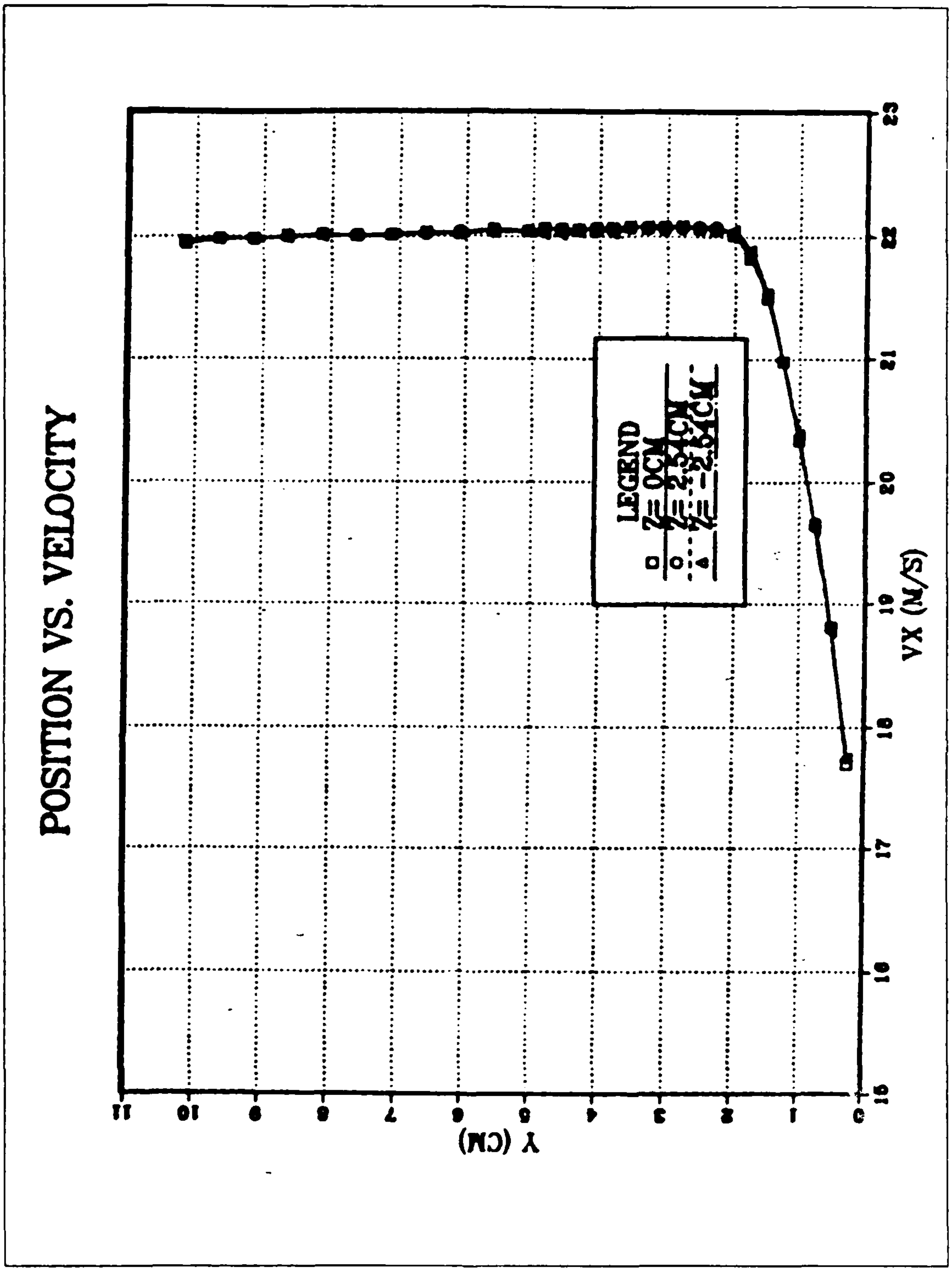


Figure 4.1 Baseline boundary layer results for streamwise velocity, V_X.

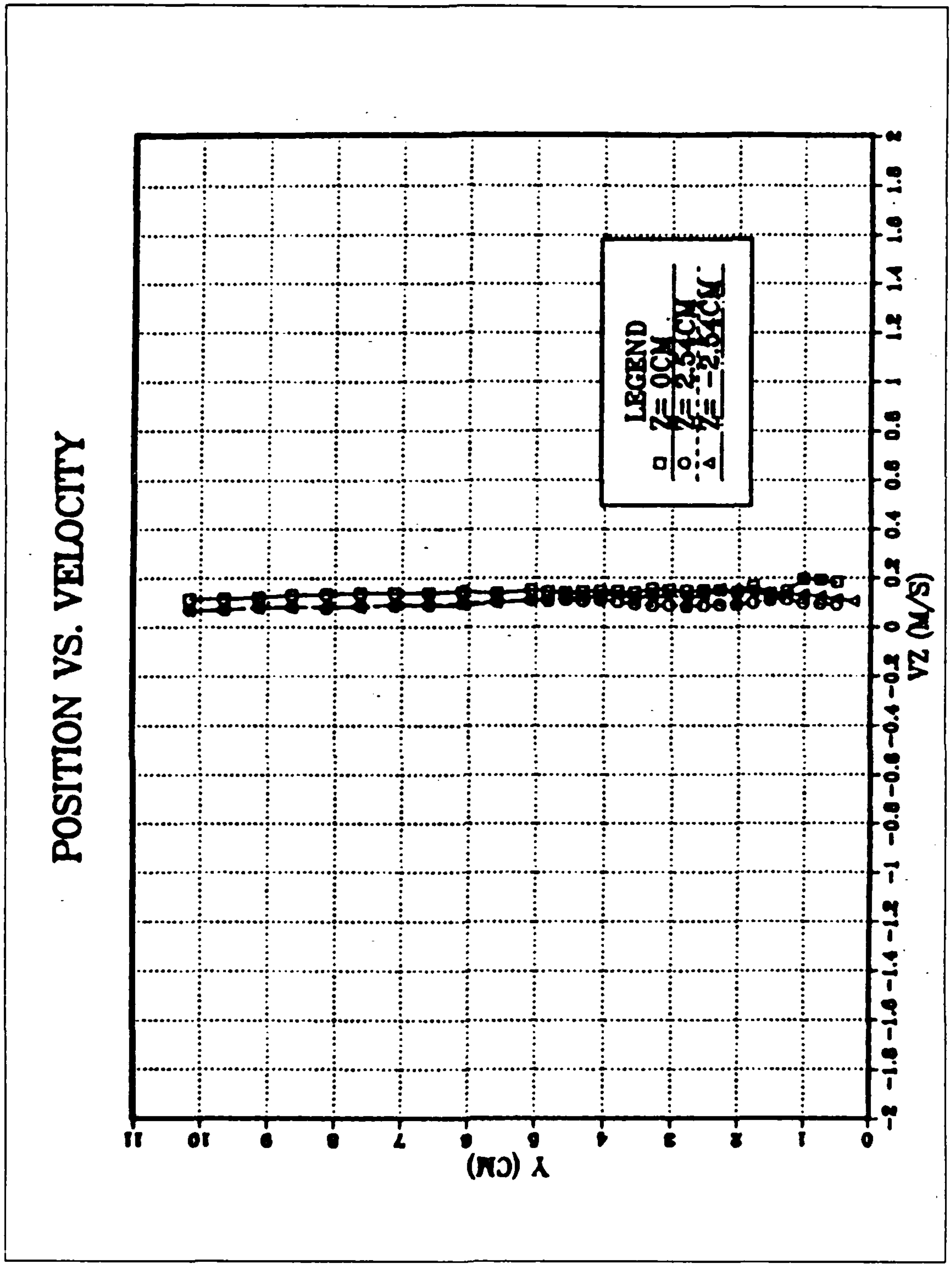


Figure 4.2 Baseline boundary layer results for spanwise velocity, V_Z.

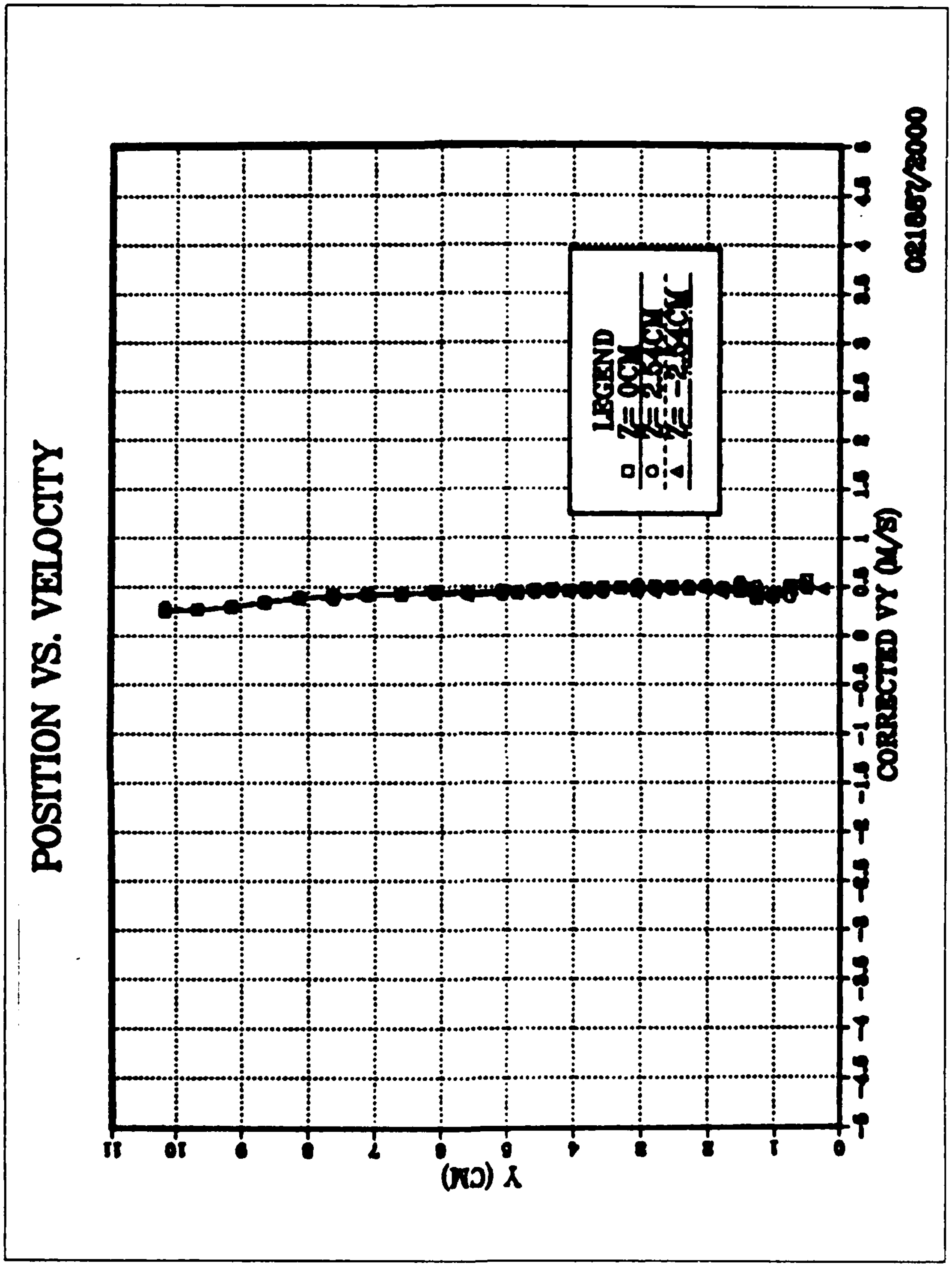


Figure 4.3 Baseline boundary layer results for corrected V_y.

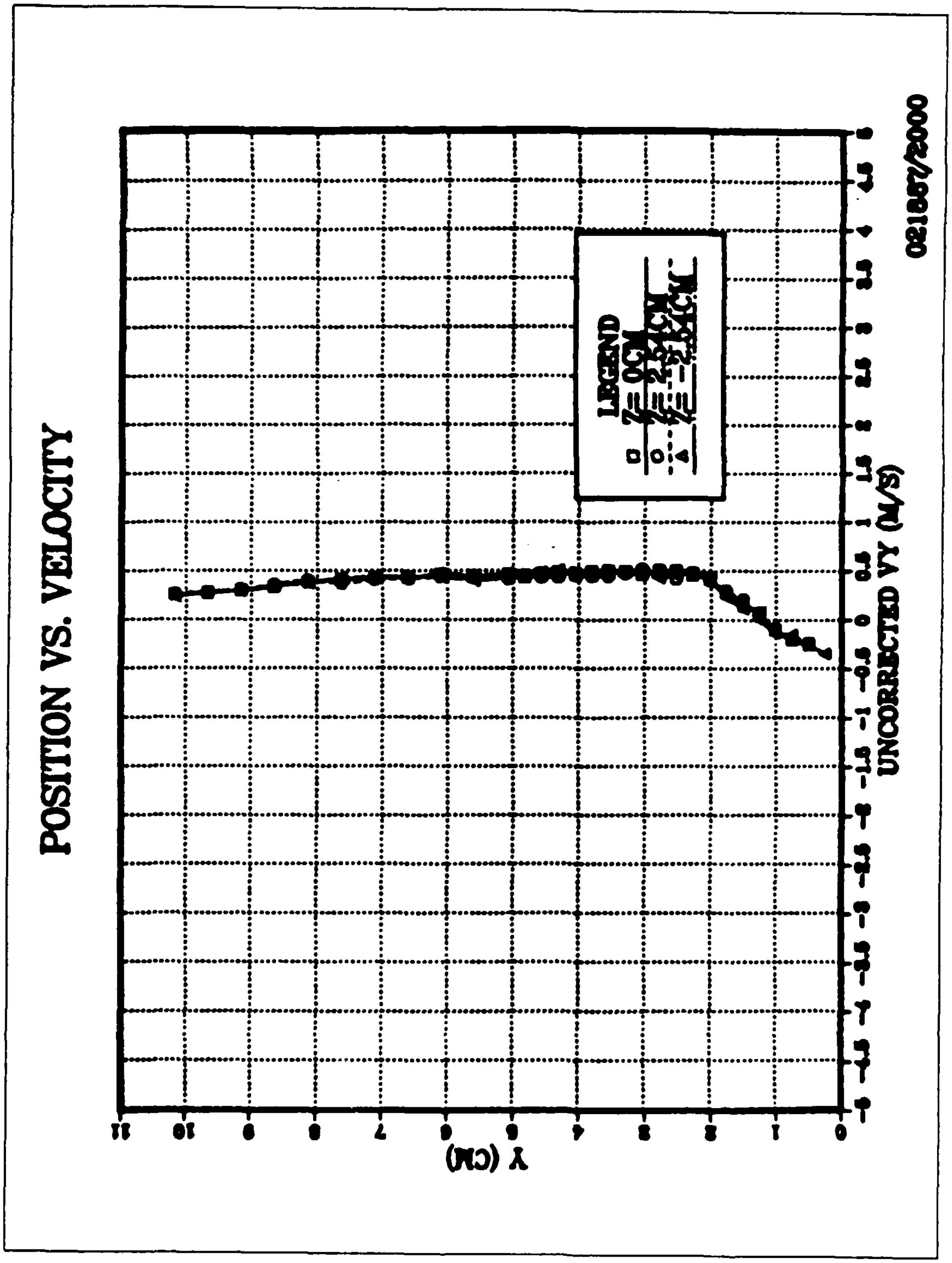


Figure 4.4 Baseline boundary layer results for uncorrected V_y.

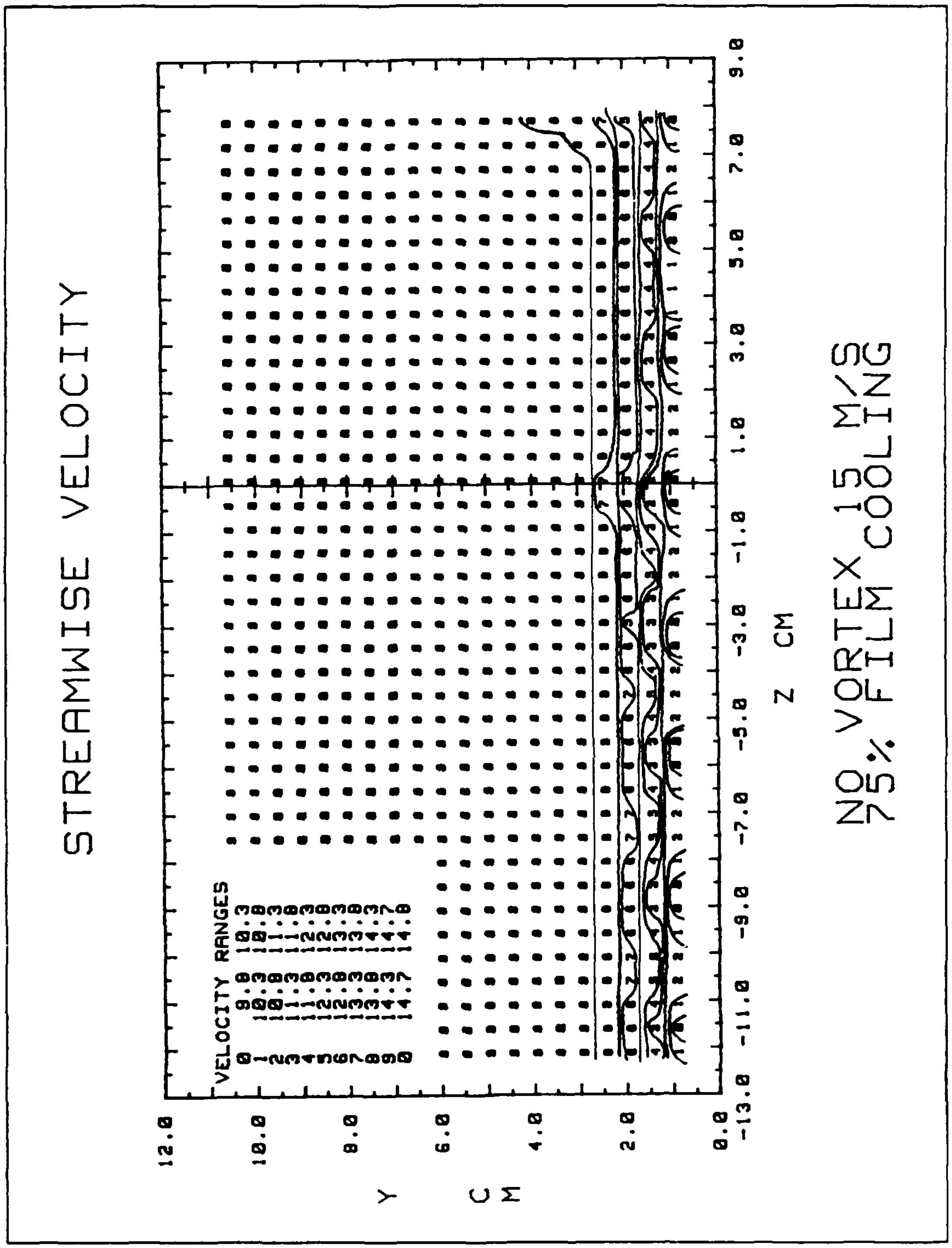


Figure 4.5 Streamwise velocity for boundary layer without embedded vortex, 75% film cooling, freestream velocity 15 m/s.

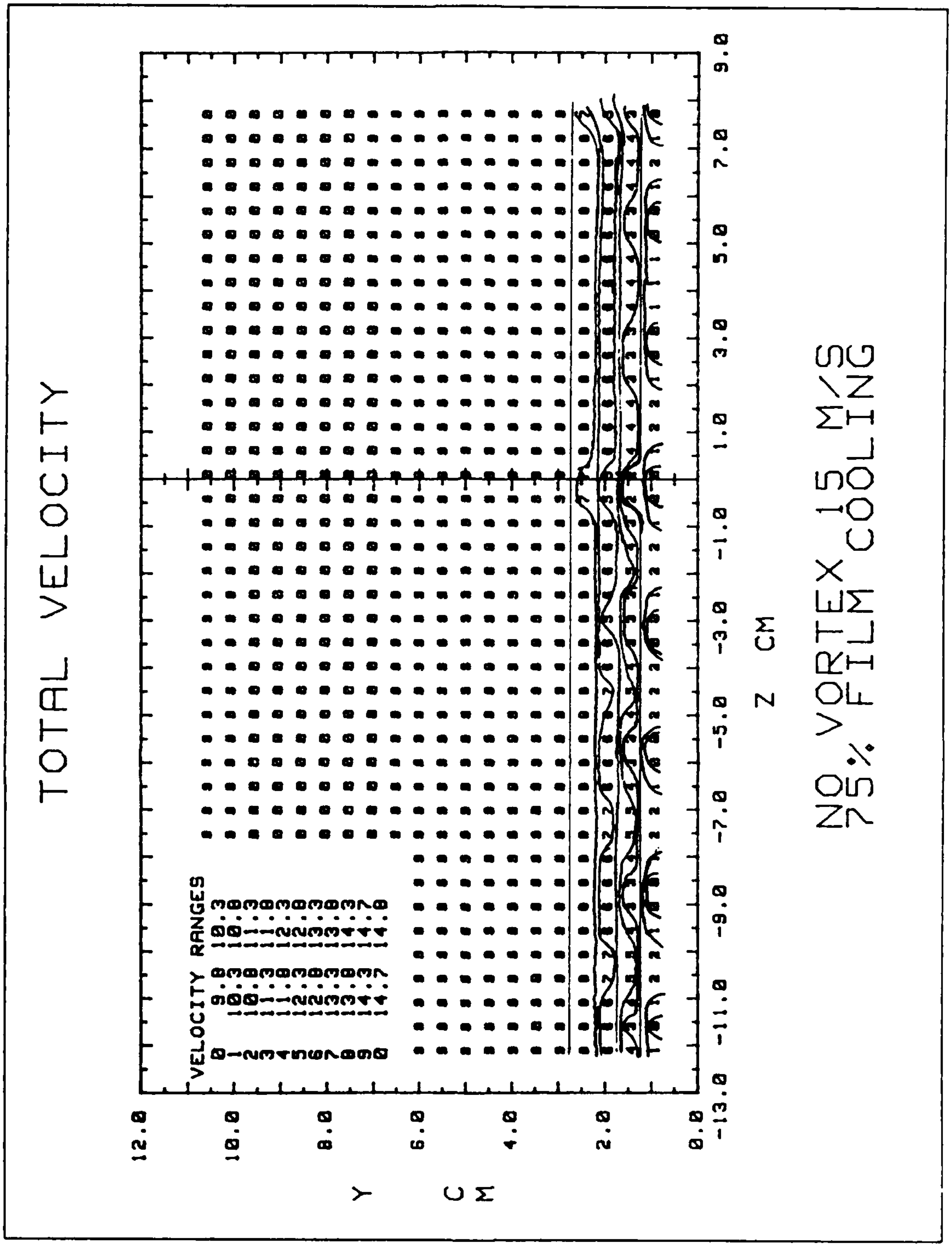


Figure 4.6 Total velocity for boundary layer without embedded vortex 75% film cooling, freestream velocity 15 m/s.

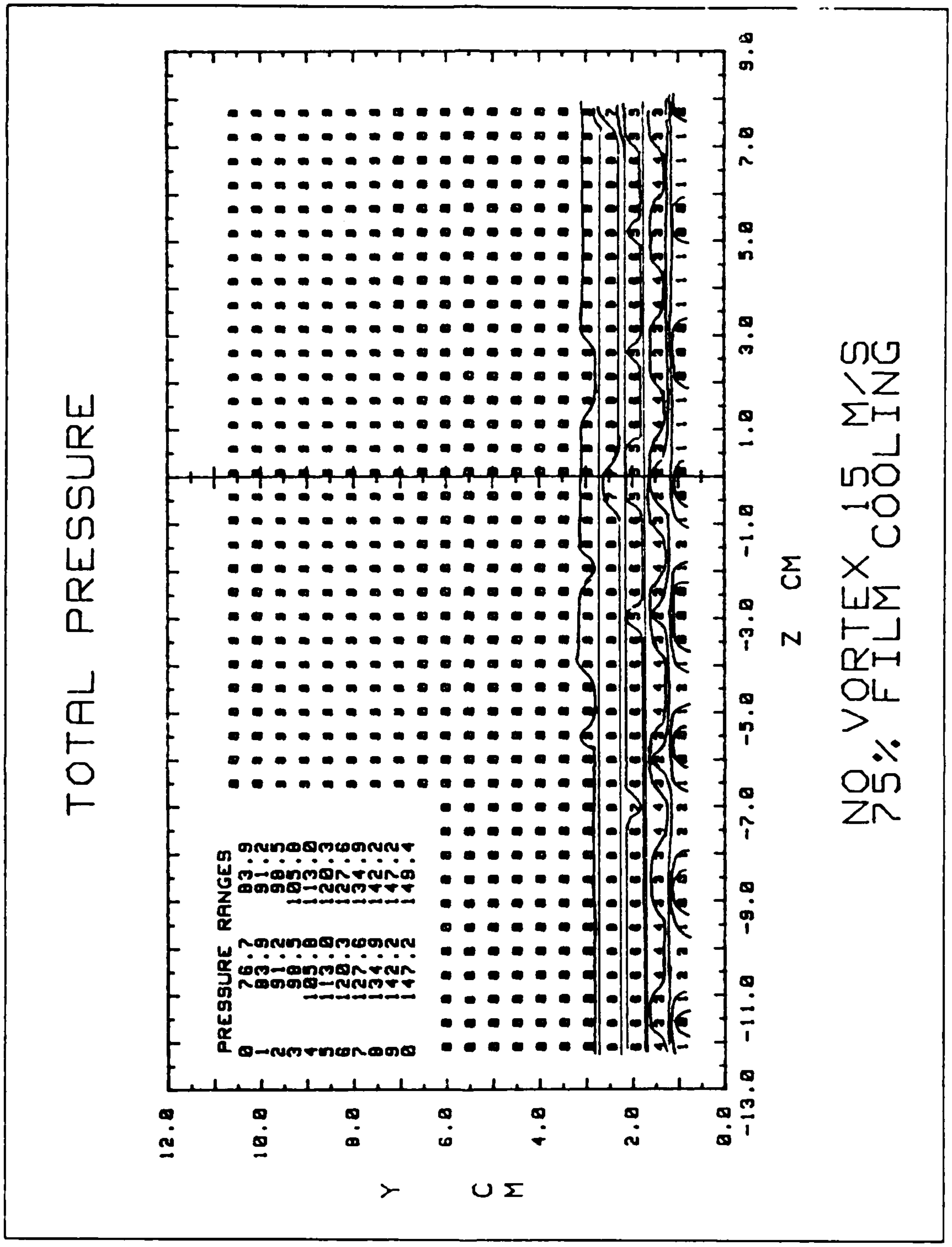


Figure 4.7 Total pressure for boundary layer without embedded vortex, 75% film cooling, freestream velocity 15 m/s.

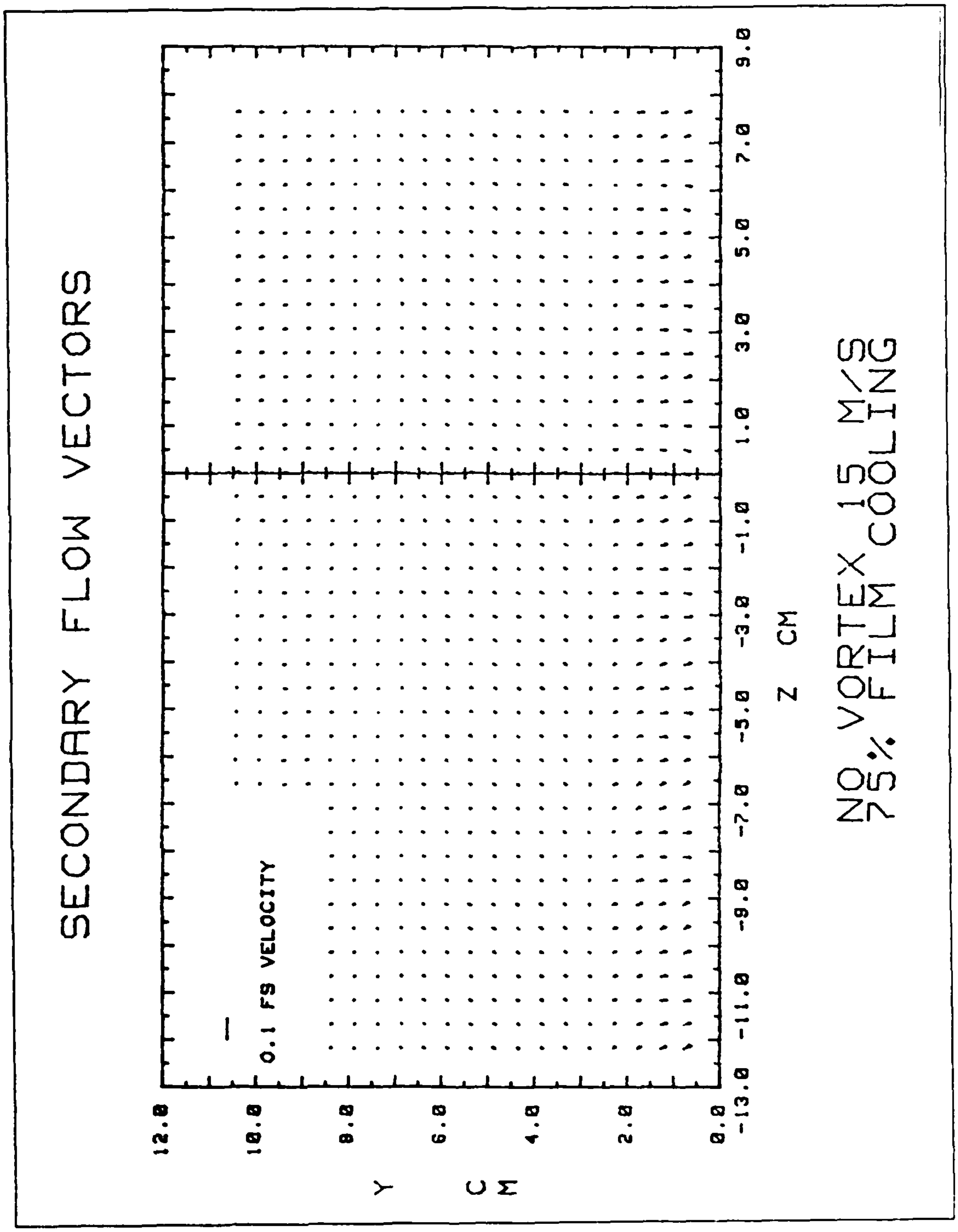


Figure 4.8 Secondary flow vectors for boundary layer without embedded vortex, 75% film cooling, freedtream velocity 15 m/s.

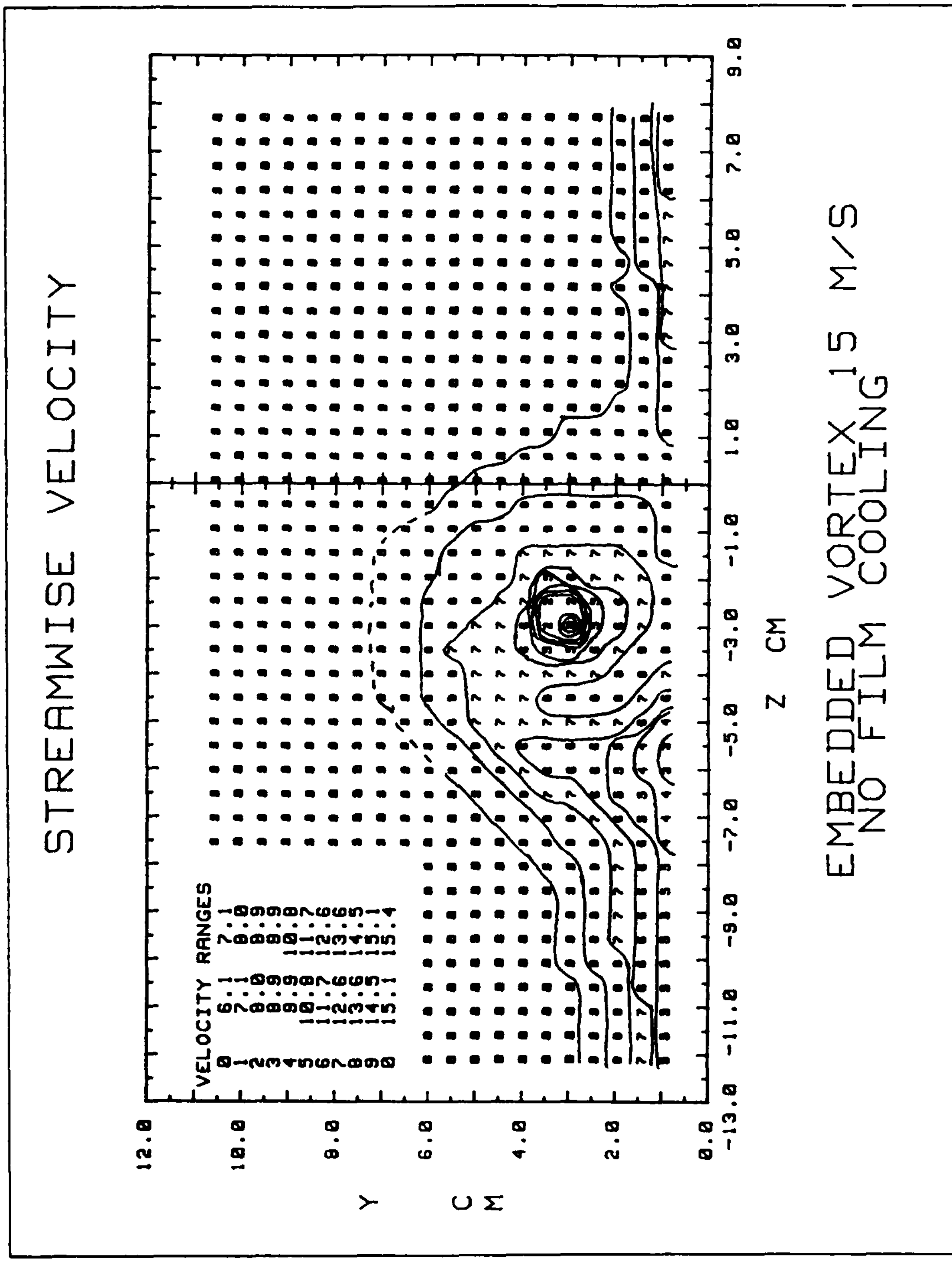


Figure 4.9 Streamwise velocity for boundary layer with embedded vortex, without film cooling, freestream velocity 15 m/s.

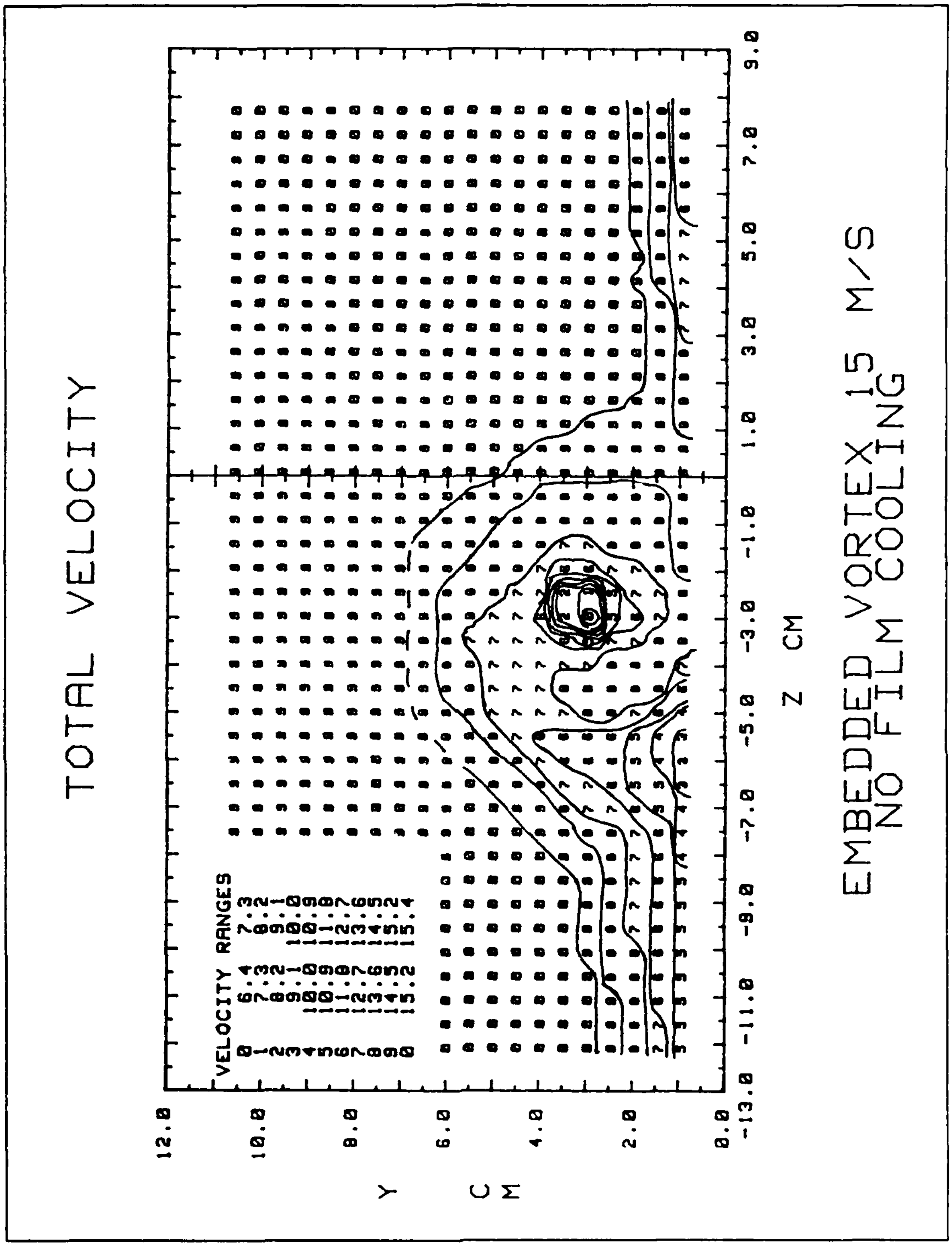


Figure 4.10 Total velocity for boundary layer with embedded vortex, without film cooling, freestream velocity 15 m/s.

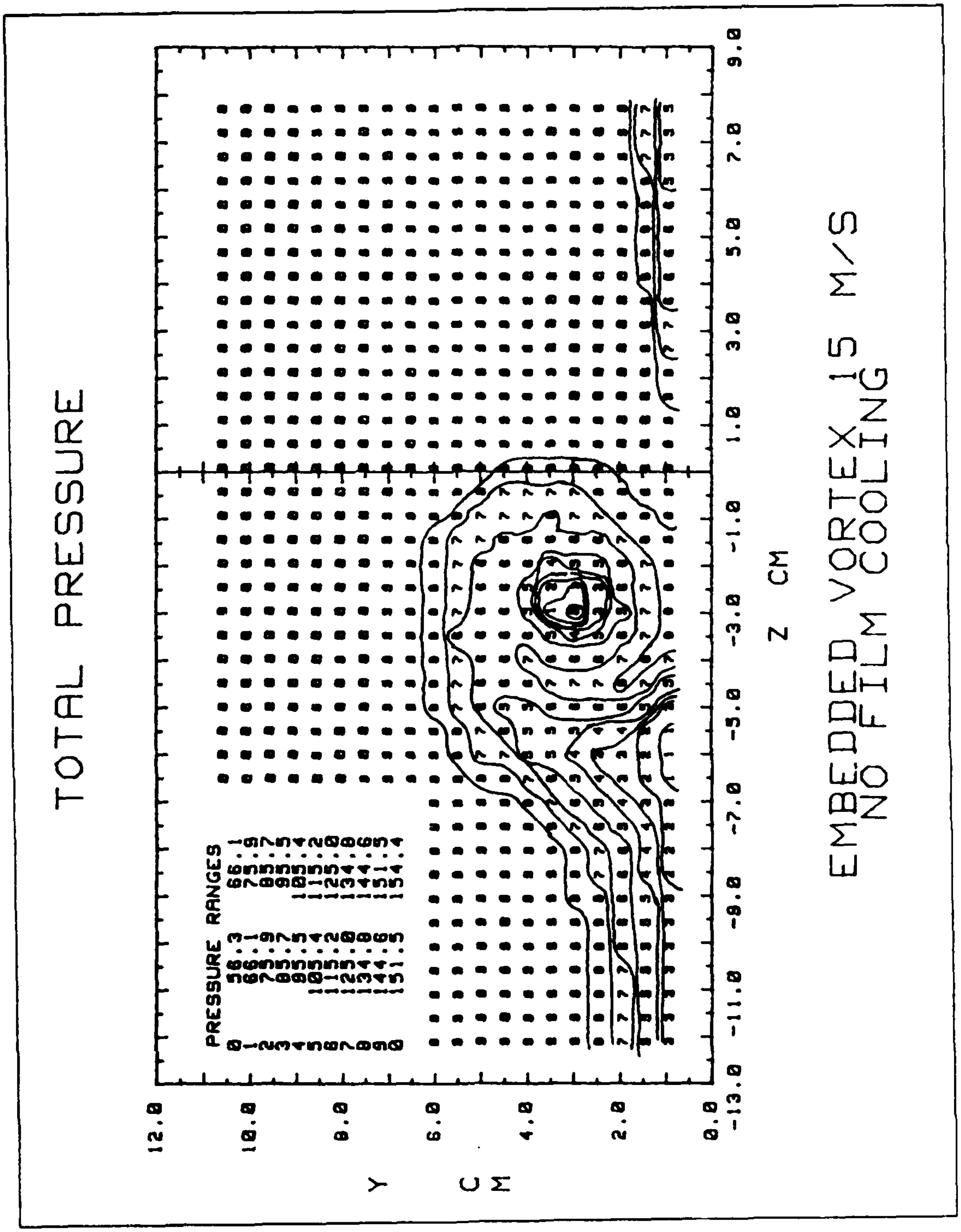


Figure 4.11 Total pressure for boundary layer with embedded vortex, without film cooling, freestream velocity 15 m/s.

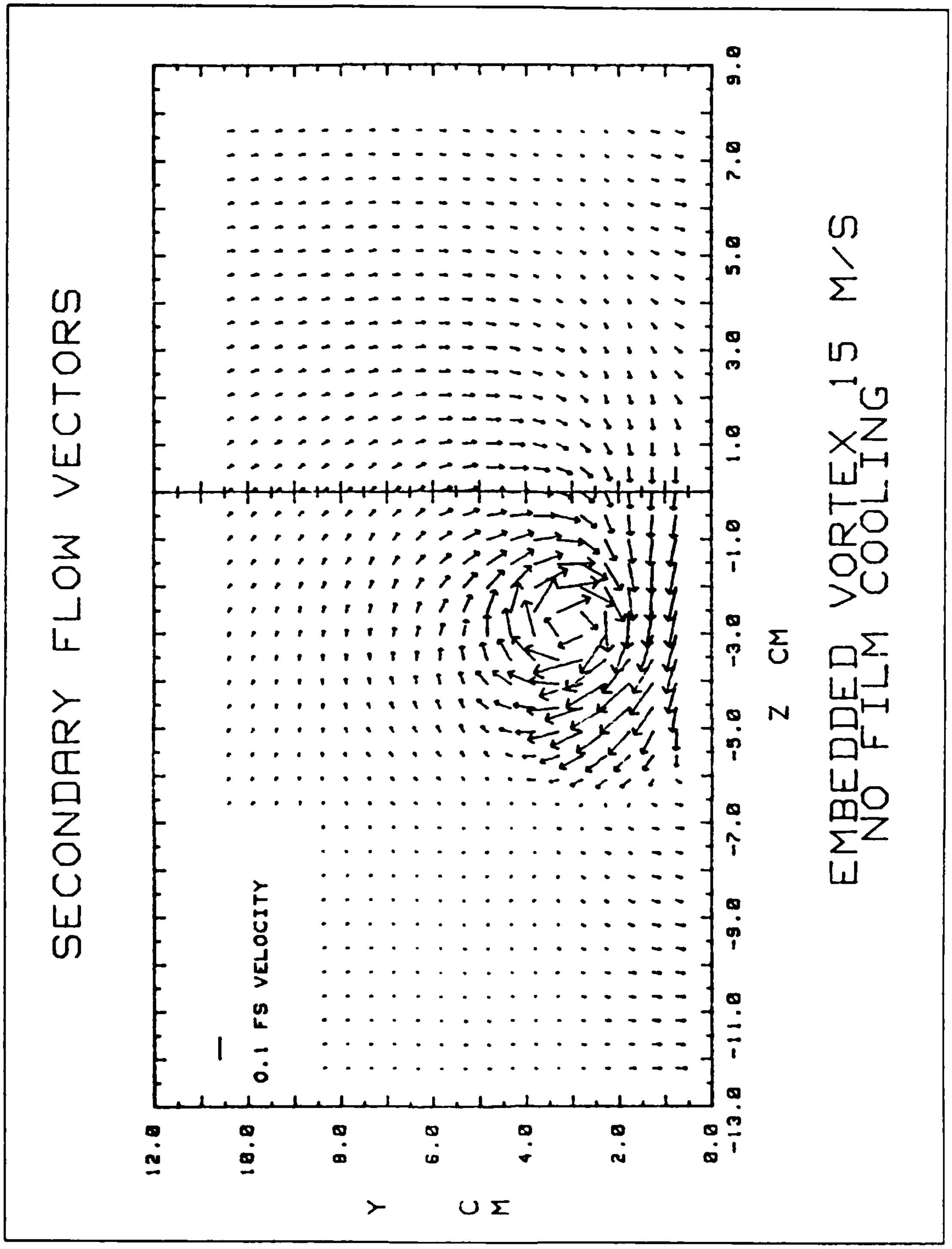


Figure 4.12 Secondary flow vectors for boundary layer with embedded vortex, without film cooling, freestream velocity 15 m/s.

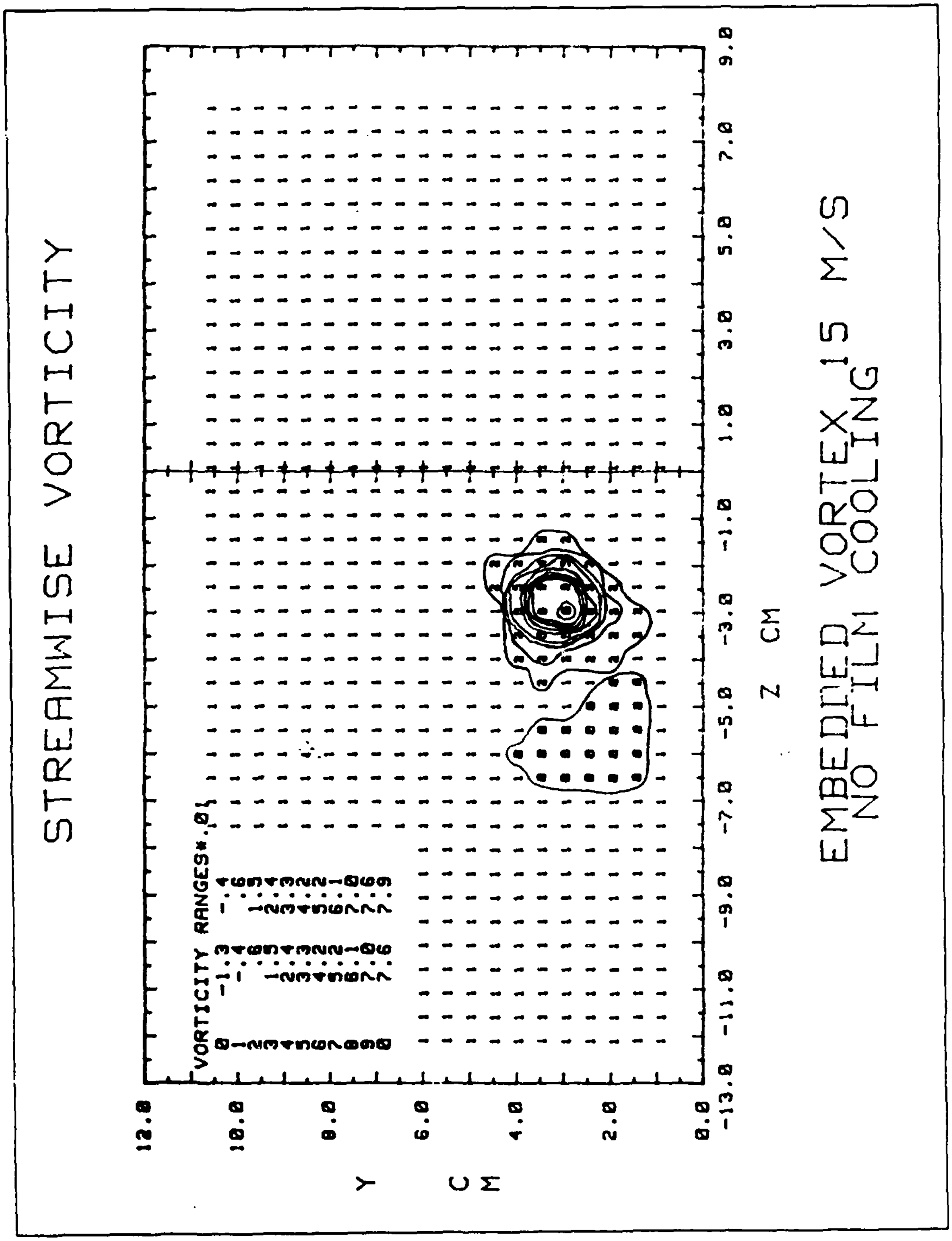


Figure 4.13 Vorticity contours for boundary layer with embedded vortex, without film cooling, freestream velocity 15 m/s.

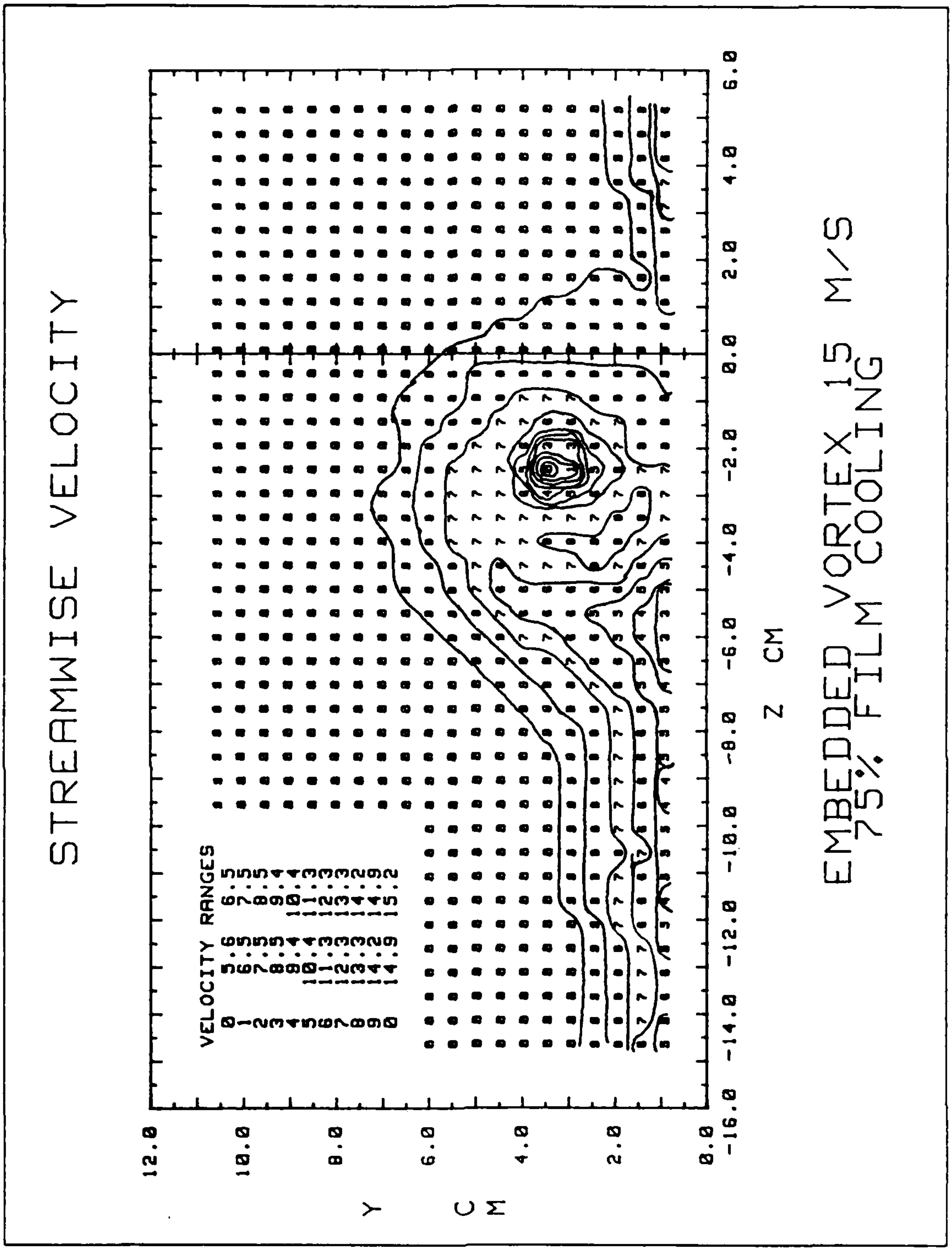


Figure 4.14 Streamwise velocity for boundary layer with embedded vortex and film cooling, freestream velocity 15 m/s.

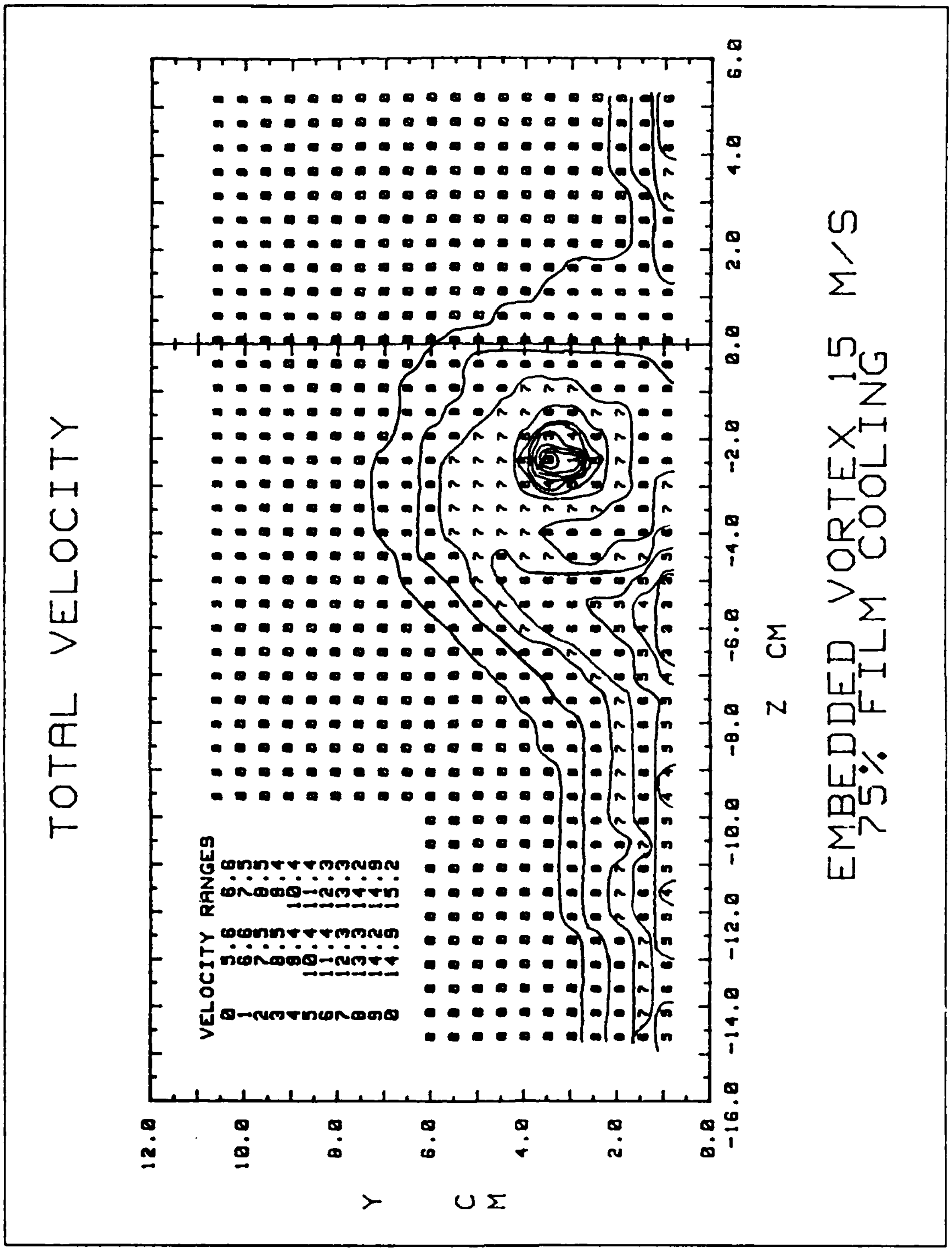


Figure 4.15 Total velocity for boundary layer with embedded vortex and film cooling, freestream velocity 15 m/s.

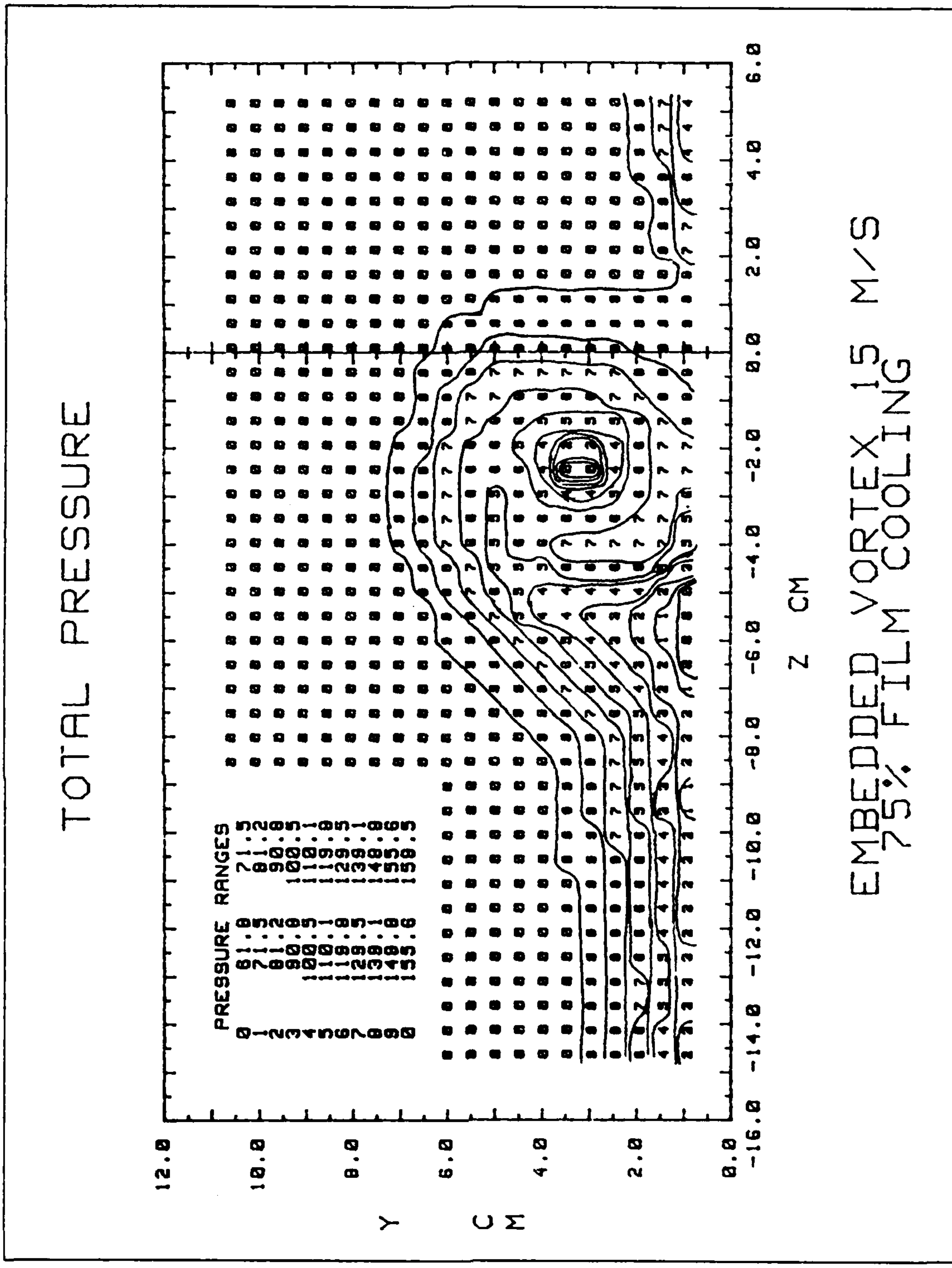


Figure 4.16 Total pressure for boundary layer with embedded vortex and film cooling, freestream velocity 15 m/s.

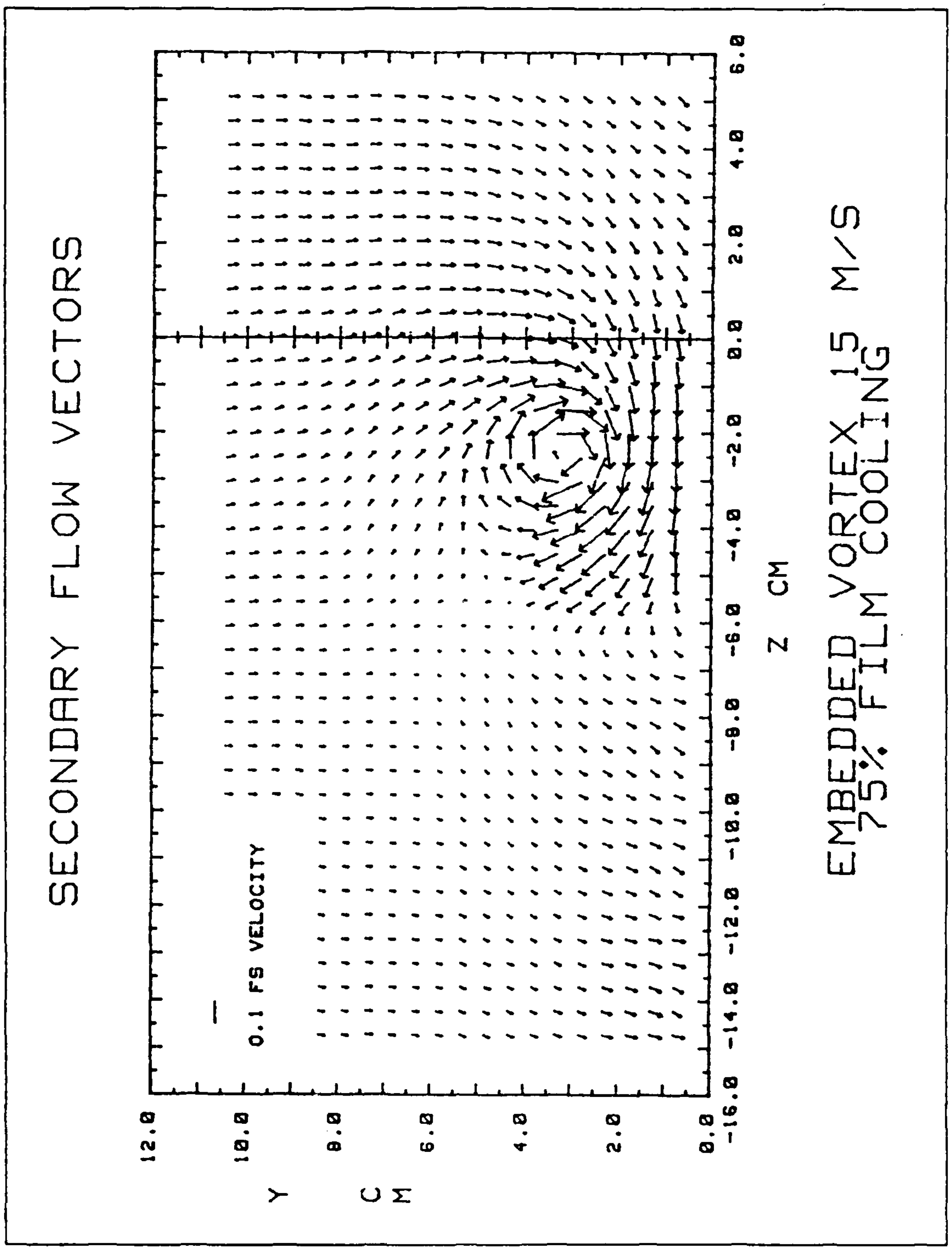


Figure 4.17 Secondary flow vectors for boundary layer with embedded vortex and film cooling, freestream velocity 15 m/s.

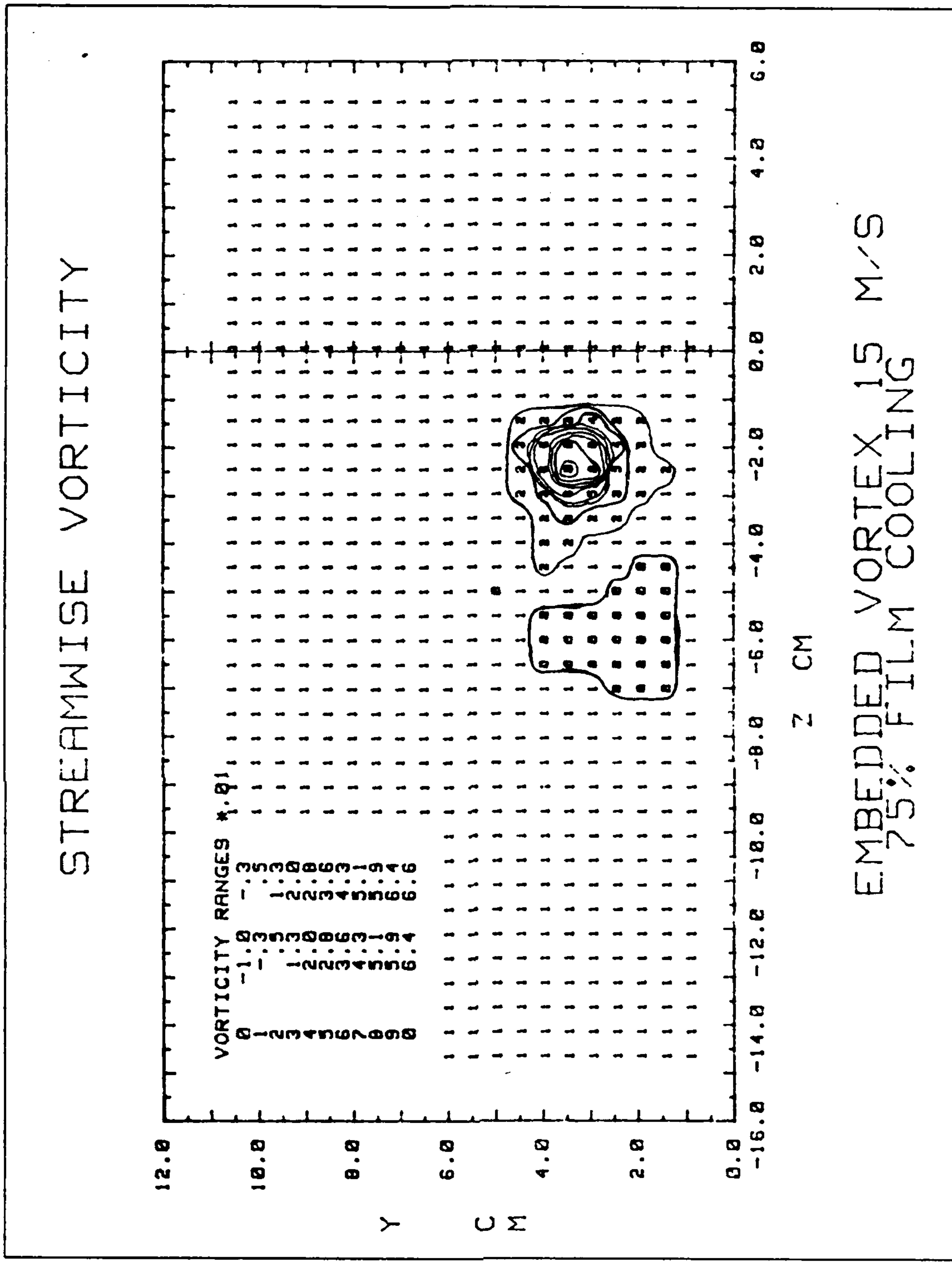


Figure 4.18 Vorticity contours for boundary layer with embedded vortex and film cooling, freestream velocity 15 m/s.

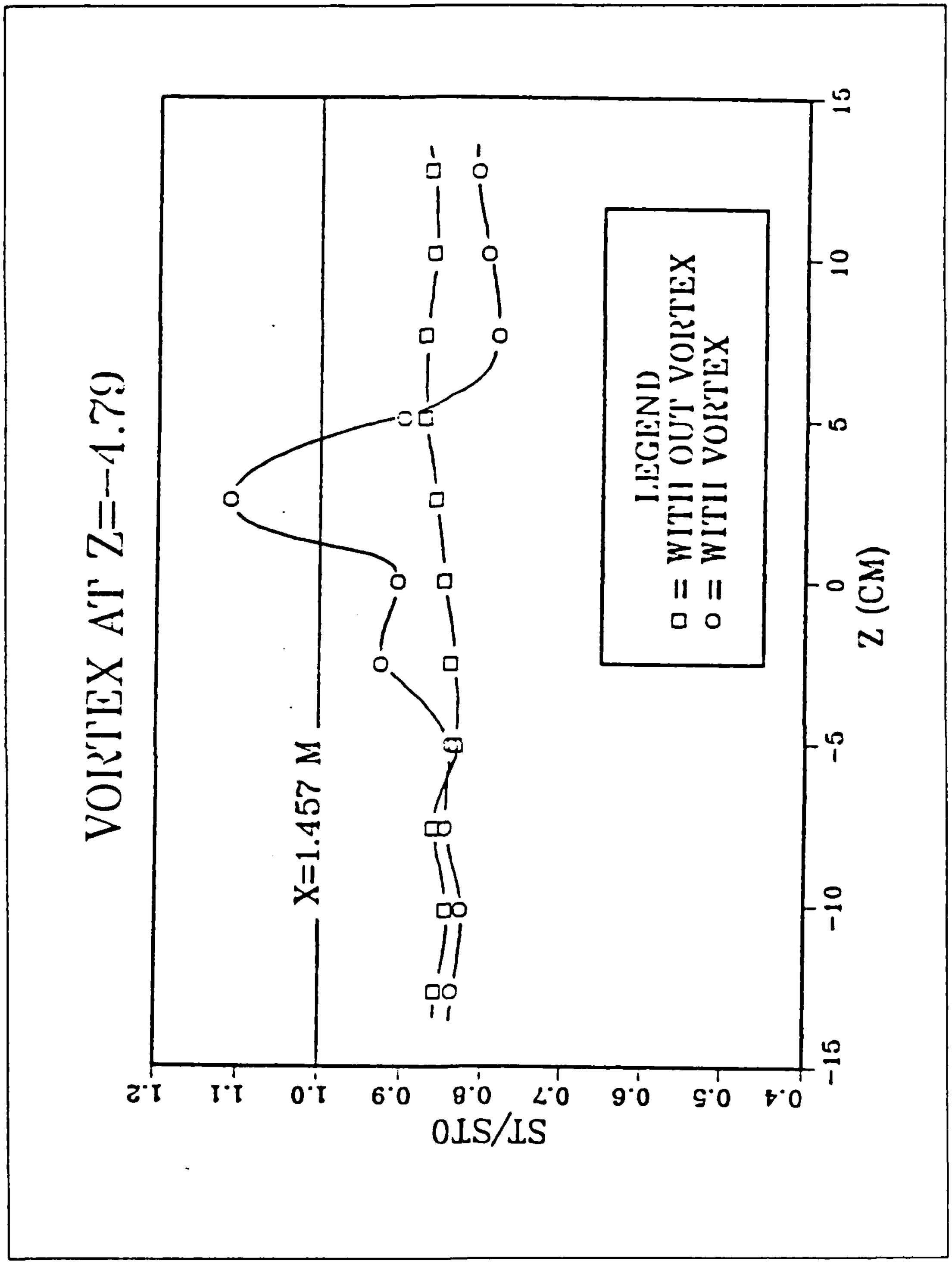


Figure 4.19 Stanton number ratio for vortex at z= -4.79cm with film cooling.

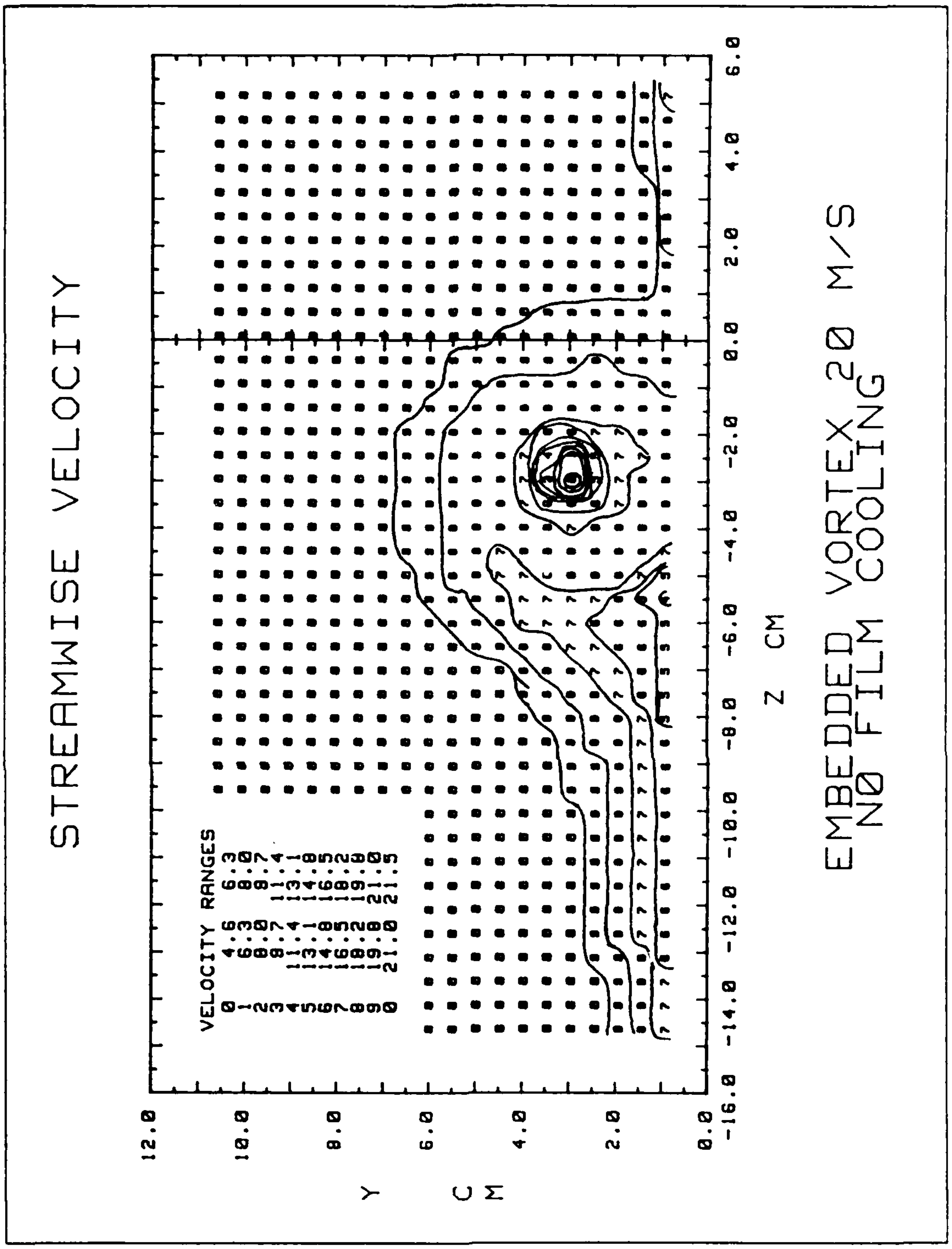


Figure 4.20 Streamwise velocity for embedded vortex without film cooling , freestream velocity 20 m/s.

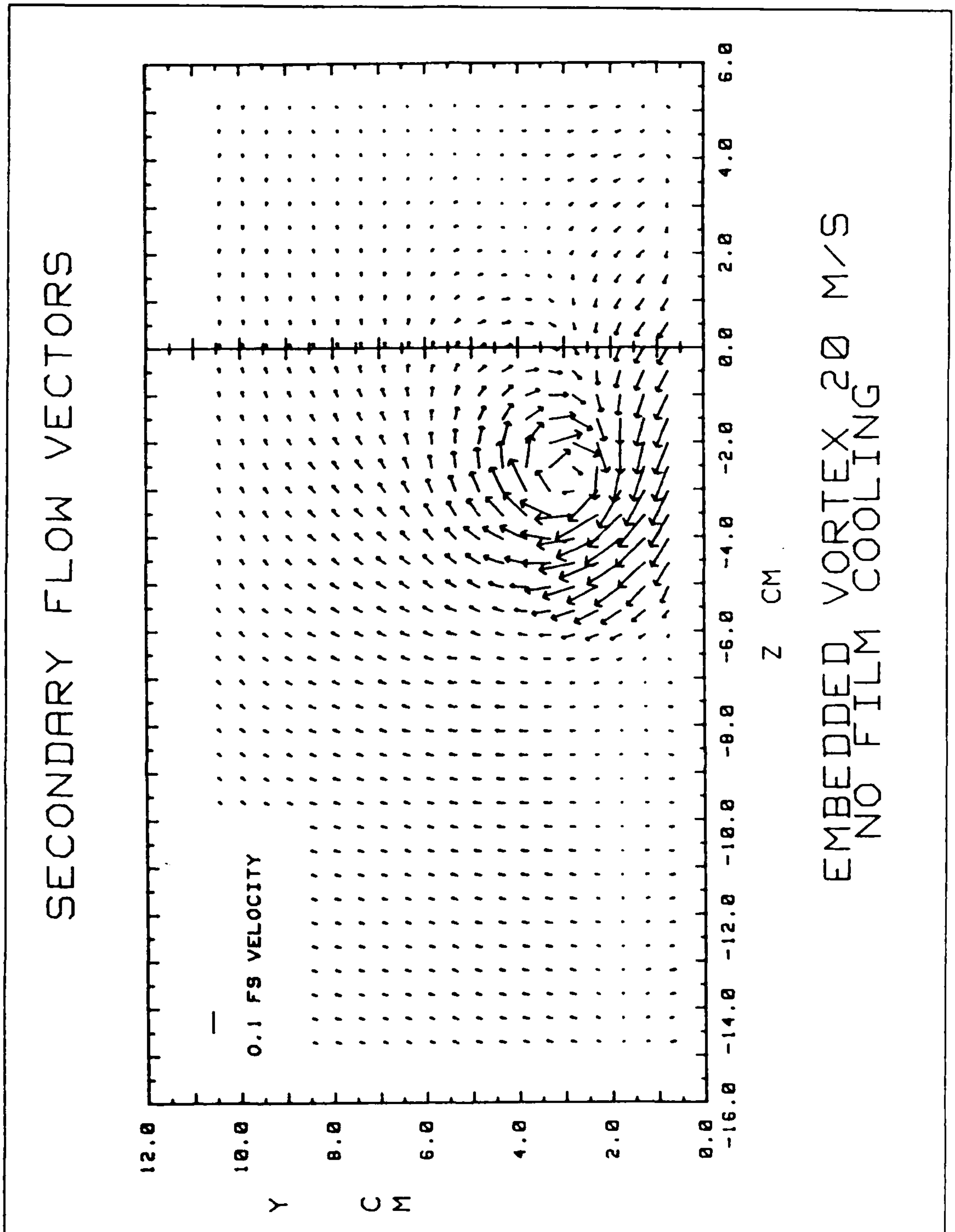


Figure 4.21 Secondary flow vectors for embedded vortex without filmcooling, freestream velocity 20 m/s.

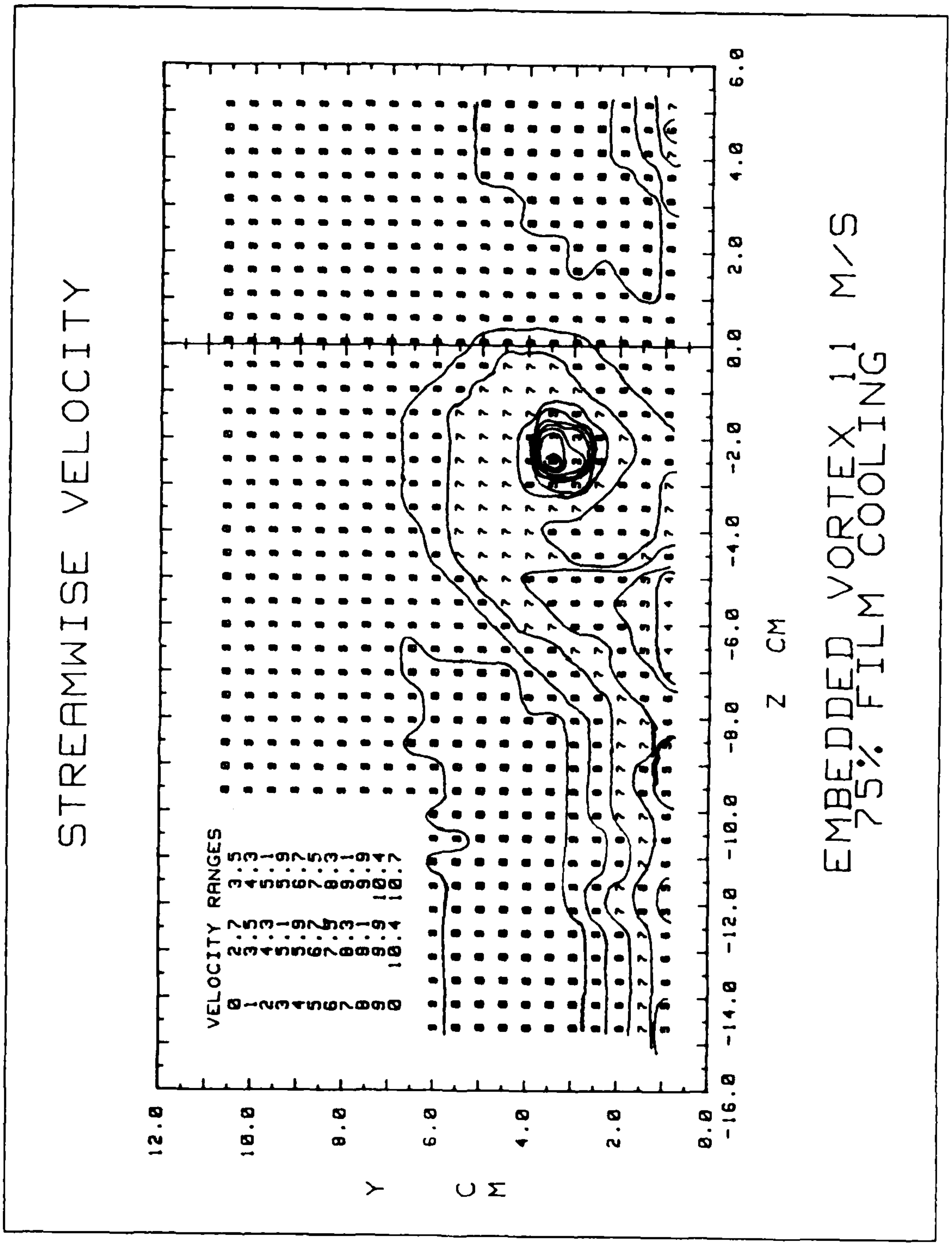


Figure 4.22 Streamwise velocity for embedded vortex with film cooling, freestream velocity 11 m/s.

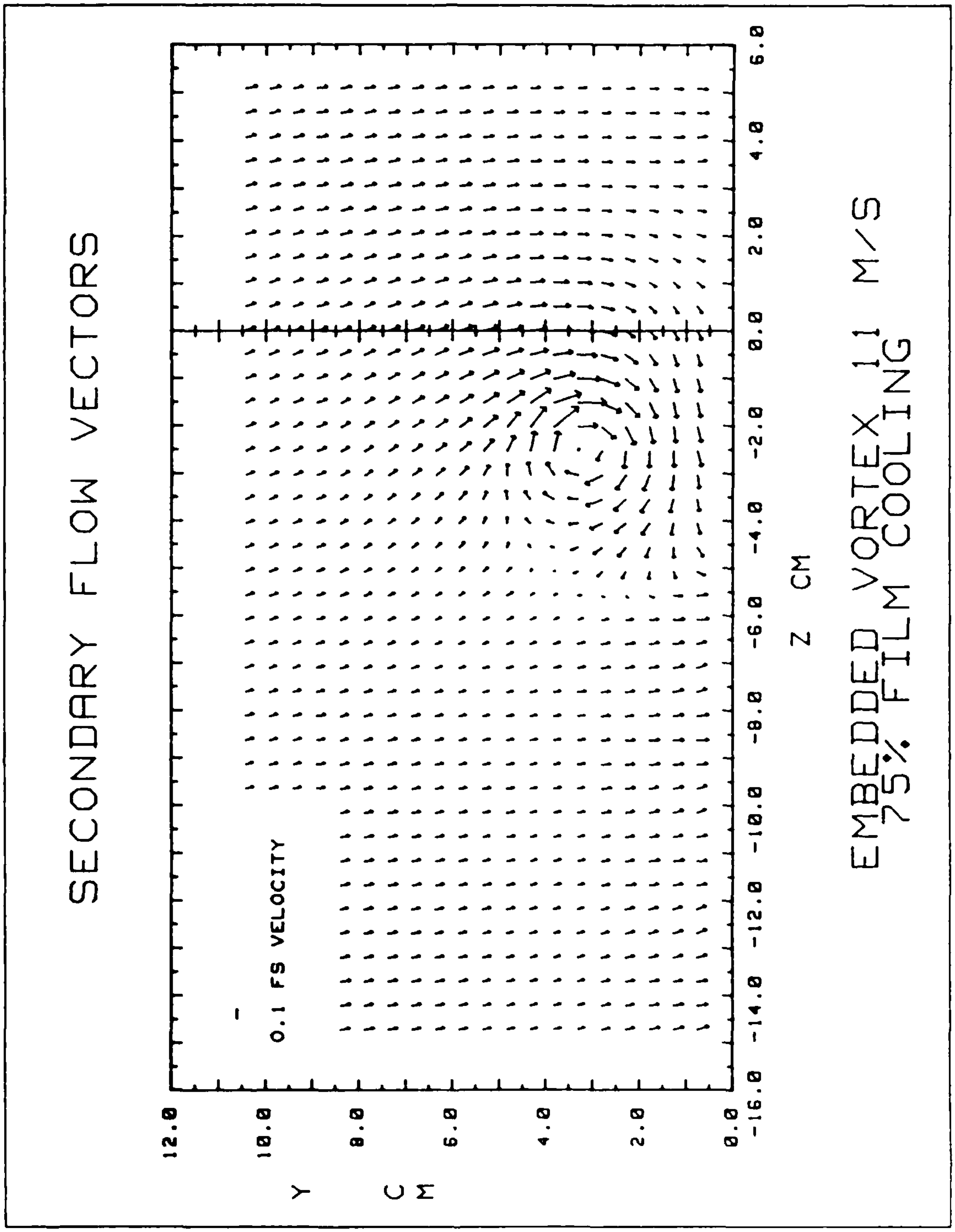


Figure 4.23 Secondary flow vectors for embedded vortex with film cooling, freestream velocity 11 m/s.

APPENDIX C
SOFTWARE

```
10 REM PROGRAM PROCAL
20 REM THIS PROGRAM COMPUTES
30 REM THE COEFFICIENTS OF YAW
40 REM AND PITCH FOR THE FIVE
50 REM HOLE PRESSURE PROBE
60 REM
70 REM DAVID EVANS   NOV 1986
80 REM
90 REM VARIABLE NAMES
100 REM
110 REM E(I) IS THE VOLTAGE
120 REM  READ FROM THE DATA
130 REM  ACQUISTION SYSTEM
140 REM
150 REM A(I) IS THE CONVERSION
160 REM FROM VOLTAGE TO INCHES
    155 REM  OF WATER
170 REM
180 REM P(I) WHERE I=1 TO 5
190 REM  ARE THE PRESSURES
200 REM  FROM THE 5 HOLES
210 REM  OF THE PRESSURE PROBE
220 REM
230 REM P6=STATIC PRESSURE
240 REM P7=TOTAL PRESSURE
250 REM P(6)=AVERAGE PRESSURE
260 REM D1= P2-P3
270 REM D2=P4-P5
280 REM D3=P1-P(6)
290 REM C1= YAW COEFFICIENT
300 REM C2 = PITCH COEFFICIENT
310 REM C3=COEFFICIENT OF TOTAL
320 REM      PRESSURE
330 REM C4=COEFFICIENT OF STATIC
               PRESSURE
340 REM
350 DIM C1(100),C2(100),C3(100)
360 DIM C4(100),X1(100),Y(100)
370 REM
380 DISP "ENTER DATE,(MMDDYY)"
390 INPUT M1
400 DISP "ENTER TIME,(HHMM)"
410 INPUT M2
420 REM
430 PRINT M1,,M2
440 REM
450 CREATE "CALDA1",2
460 ASSIGN# 1 TO "CALDA1"
470 ! PRINT# 1 ; M1,M2
480 REM
```

```
490 REM THIS SECTION COMPUTES
500 REM THE CONVERSION FACTOR
510 REM FOR VOLTAGE TO INCHES
520 REM OF WATER THE USER MUST
530 REM INPUT THE MANOMETER
540 REM
550 REM THIS SECTION COMPUTES
    615 REM  THE ZERO OFFSET COR
    -    616 REM  RECTION FOR THE
     TRANS-
560 REM  THE ZERO OFFSET COR-
    622 REM  RECTION FOR THE TRA
    NS- 623 REM
570 REM
580 DISP "COMPUTE ZERO OFFSET "
590 DISP "CORRECTION "
600 DISP " !!! DISCONNECT ALL
                TUBING TO THE TRA
    NS              DUCERS!!!"
610 DISP " HIT CONT  WHEN READY"
620 PAUSE
630 CLEAR
640 FOR I=200 TO 204
650 Z2=0
660 FOR J=1 TO 50
670 OUTPUT 709 ;"AI";I;"VT1"
680 ENTER 709 ; X2
690 Z2=Z2+X2
700 NEXT J
710 Z3=Z2/50
720 Z4(I-199)=Z3
730 NEXT I
740 REM
750 REM
760 REM *******LOOP#1*********
770 REM
780 FOR I=200 TO 204
790 I1=I-199
800 DISP "TRANSDUCER CALIBRATION
              ENTER THE MANOMETE
    R                PRESSURE (IN
     H2O)"
810 DISP "ENTER THE PRESSURE"
820 DISP "TRANSDUCER NP ",I1
830 INPUT H2
840 Z0=0
850 REM
860 REM *****LOOP#2**********
870 FOR J=1 TO 50
880 OUTPUT 709 ;"AI";I;"VT1"
890 ENTER 709 , X
900 Z0=Z0+X
910 NEXT J
920 REM *********************
```

```
930 E1=Z0/50
940 A(I-199)=H2/(E1-Z4(I-199))
950 PRINT "A",I,"=",A(I-199)
960 DISP "IF A(I) IS UNSAT
              PRESS 8 "
970 INPUT N2
980 IF N2=8 THEN GOTO 800
990 NEXT I
1000 REM
1010 REM **********************
1020 REM
1030 REM ENTER THE VALUES OF
1040 REM  STATIC AND TOTAL
1050 REM   PRESSURE.
1060 REM
1070 DISP "INPUT STATIC PRESSURE
     ,           (INCHES OF H2O)"
1080 DISP "USE TRANSDUCER NR 1"
1090 DISP "AND CHANNEL NR. 200"
1100 REM
1110 DISP "HIT CONTINUE WHEN"
1120 DISP "P STATIC PROPERLY"
1130 DISP "HOOKED UP."
1140 PAUSE
1150 CLEAR
1160 B6=0
1170 FOR J=1 TO 50
1180 REM
1190 OUTPUT 709 ;"AI",200;"VT1"
1200 ENTER 709 ; X6
1210 B6=B6+X6
1220 NEXT J
1230 P6=B6/50
1240 REM
1250 DISP "INPUT THE TOTAL PRES-
                SURE,(INCHES H2
     O)"
1260 DISP " AND CHANNEL NR 200"
1270 DISP "                 "
1280 DISP " HIT CONTINUE WHEN"
1290 DISP " P TOTAL PROPERLY"
1300 DISP " HOOKED UP "
1310 PAUSE
1320 CLEAR
1330 REM
1340 B7=0
1350 FOR J=1 TO 50
1360 OUTPUT 709 ;"AI",200;"VT1"
1370 ENTER 709 ; X7
```

```
1380 B7=B7+X7
1390 NEXT J
1400 P7=B7/50
1410 REM
1420 REM
1430 REM ENTER AMBIENT CONDITION
     S
1440 REM
1450 DISP "ENTER PAMB(IN.HG)"
1460 INPUT A1
1470 REM
1480 T=0
1490 FOR J=1 TO 50
1500 OUTPUT 709 ;"AI";109;"VTI"
1510 ENTER 709 ; T1
1520 T=T+T1
1530 NEXT J
1540 T3=T/50
1550 GOSUB 3010
1560 REM
1570 REM DEL P COMPUTED FROM
1580 REM  PTOTAL-PSTATIC
1590 REM
1600 C=P7-P6
1610 REM
1620 REM
1630 REM CONVERSION TO SI UNITS
1640 A1=A1*3385.82
```

```
1650 C=C*248.7
1660 T4=T3+273.15
1670 R1=A1/(.287*T4)
1680 U1=(2*C/R1)^.5
1690 REM
1700 REM
1710 REM ENTER THE BIG LOOP
1720 REM FOR READING PRESSURES
1730 REM AND COMPUTING COEFF
1740 REM
1750 REM ******LOOP#3***********
1760 FOR K=1 TO 100
1770 K1=K
1780 REM ENTER THE VALUE OF THE
1790 REM PITCH ANGLE AND YAW
1800 REM
1810 DISP " ENTER THE VALUE OF
               THE PITCH ANGLE"
1820 INPUT X1(K)
1830 REM
1840 DISP "ENTER THE VALUE OF"
1850 DISP "THE YAW ANGLE "
```

```
1860 INPUT Y(K)
1870 DISP " PITCH ANGLE ENTERED
           IS",X1(K)
1880 DISP "YAW ANGLE ENTERED IS
           ",Y(K)
1890 DISP "      "
1900 DISP " DO YOU WANT TO CHANG
     E          PITCH OR YAW IF
     SO PRE            SS 1"
1910 INPUT N4
1920 IF N4=1 THEN 1800
1930 REM THIS LOOP ACQUIRES EACH
1940 REM PRESSURE 50 TIMES AND
1950 REM TAKES THE AVERAGE.
1960 REM
1970 DISP "HIT 'CONTINUE' FOR"
1980 DISP "DATA ACQUISITION."
1990 PAUSE
2000 CLEAR
2010 REM
2020 REM *****LOOP#3*********
2030 FOR I=200 TO 204
2040 Z1=0
2050 REM *****LOOP#4*********
2060 FOR J=1 TO 50
2070 OUTPUT 709 ;"AI";I;"VT1"
2080 ENTER 709 ; X
2090 Z1=Z1+X
2100 NEXT J
2110 REM **********************
2120 X=Z1/50
2130 E(I-199)=X
2140 P(I-199)=A(I-199)*E(I-199)-
     Z4(I-199)
2150 NEXT I
2160 REM ***********************
2170 REM
2180 P(6)=0
2190 FOR I=2 TO 5
2200 P(6)=P(I)+P(6)
2210 NEXT I
2220 P(5)=P(6)/4
2230 D1=P(2)-P(3)
2240 D2=P(4)-P(5)
2250 D3=P(1)-P(6)
2260 C1(K)=D1/D3
2270 C2(K)=D2/D3
2280 C3(K)=(P(1)-P7)/D3
2290 C4(K)=(P(6)-P6)/D3
```

```
2300 REM
2310 PRINT# 1 ; X1(K),Y(K),C1(K)
     ,C2(K),C3(K),C4(K)
2320 REM
2330 REM
2340 PRINT "PITCH ANGLE IS",X1(K
     )
2350 PRINT "YAW ANGLE IS",Y(K)
2360 PRINT
2370 PRINT "P1=",P(1)
2380 PRINT "P2=",P(2)
2390 PRINT "P3=",P(3)
2400 PRINT "P4=",P(4)
2410 PRINT "P5=",P(5)
2420 PRINT
2430 PRINT
2440 DISP "LAST POINT??"
2450 DISP "IF SO PRESS 1"
2460 INPUT N1
2470 IF N1=1 THEN GOTO 2500
2480 NEXT K
2490 REM ***********************
     1705
2500 REM
2510 ASSIGN# 1 TO *
2520 REM
2530 PRINT
2540 PRINT "*********************
     ********"
2550 PRINT
2560 PRINT
2570 PRINT "FIVE HOLE PRESSURE
                 PROBE CALIBRAT
     ION."
2580 PRINT
2590 PRINT
2600 PRINT "DATE OF RUN IS",M1
2610 PRINT "TIME OF RUN IS",M2
2620 PRINT
2630 PRINT
2640 PRINT "DENSITY(KG/M3)"
2650 PRINT R1
2660 PRINT "VELOCITY(M/S)"
2670 PRINT U1
2680 PRINT "PAMB(N/M2)"
2690 PRINT A1
2700 PRINT "TAMB(C)"
2710 PRINT T3
2720 PRINT "P STATIC (IN. H2O)"
2730 PRINT P6
2740 PRINT "P TOTAL=(IN. H2O)"
2750 PRINT P7
2760 PRINT
2770 PRINT "PIT YAW   CP1      C
     P2"
```

```
2780 REM *****LOOP#5**********
2790 FOR I=1 TO K1
2800 PRINT USING 2810 ; X1(I),Y(
     I),C1(I),C2(I)
2810 IMAGE MDD,2X,MDD,2X,MD.DDDD
     ,2         X,MD.DDDD
2820 NEXT I
2830 REM *********************
2840 PRINT
2850 PRINT
2860 PRINT "PIT  YAW   CP3    CP
     4"
2870 REM *****LOOP#6**********
2880 FOR I=1 TO K1
2890 PRINT USING 2900 ; X1(I),Y(
     I),C3(I),C4(I)
2900 IMAGE MDD,2X,MDD,2X,MD.DDDD
     ,2         X,MD.DDDD
2910 NEXT I
2920 REM **********************
     *
2930 PRINT
2940 DISP " THANKS FOR USING ME"
2950 DISP " HOPE YOU FOUND WHAT"
2960 DISP "YOU WERE LOOKING FOR"
2970 DISP "          REGARDS"
2980 DISP "           HP-85B"
2990 END
3000 REM
3010 REM VOLTAGE TO TEMPERATURE
3020 REM CONVERSION
3030 REM
3040 REM V(MV) TO T(C)
3050 REM
3060 E1=T2*1000
3070 T3=26.573*E1-1.936879*E1*E1
     +.99785*E1*E1*E1-.261277*E1
     *E1*E1*E1
3080 RETURN
```

```
20    REM PROGRAM PRSACQ
30    REM THIS PROGRAM ACQUIRES THE PRESSURES FROM
40    REM A FIVE HOLE PRESSURE PROBE AND COMPUTES PITCH,YAW AND
50    REM OBTAINED FROM THE PROGRAM "PROCAL"
60    REM
70    REM AUTHOR DAVE EVANS, JANUARY,FEBRUARY, 19?7
80    REM
90    REM VARIABLE NAMES
100   REM
110   REM E(I) IS THE VOLTAGE READ FROM THE DATA ACQUISITION SYSTEM
120   REM A(I) IS THE CONVERSION FROM VOLTAGE TO INCHES OF WATER
130   REM P(I) IS THE PRESSURE READ FROM THE FIVE HOLE PRESSURE PROBE
140   REM I=1 TO 5 AND IN EACH OF THE ABOVE IS ASSOCIATED WITH THE
150   REM PRESSURES FROM THE FIVE HOLE PROBE
160   REM
170   REM P6=STATIC PRESSURE OF THE FREESTREAM
180   REM P7=TOTAL PRESSURE OF THE FREESTREAM
190   REM P(6)=AVERAGE PRESSURE
200   REM D1=P2-P3
210   REM D2=P4-P5
220   REM D3=P1-P(6)
230   REM
240   REM C1=CALIBRATED YAW COEFFICIENT
250   REM C2=CALIBRATED PITCH COEFFICIENT
260   REM C3=CALIBRATED TOTAL COEFFICIENT
270   REM C4=CALIBRATED STATIC COEFFICIENT
280   REM
290   REM M1=MEASURED YAW COEFFICIENT
300   REM M2=MEASURED PITCH COEFFICIENT
310   REM M3=MEASURED TOTAL COEFFICIENT
320   REM M4=MEASURED STATIC COEFFICIENT
330   REM
340   REM V=THE LOCAL TOTAL VELOCITY VECTOR
350   REM V1=THE X COMPONENT OF VELOCITY
360   REM V2=THE Y COMPONENT OF VELOCITY
370   REM VZ=THE Z COMPONENT OF VELOCITY
380   REM
390   REM X1=THE PITCH ANGLE FROM THE CALIBRATION DATA
400   REM Y=THE YAW ANGLE FROM THE CALIBRATION DATA
410   REM
420   REM X4=THE PITCH ANGLE OF THE FLOW
430   REM
440   REM Y1=THE VERTICAL LOCATION  OF THE PROBE TIP
450   REM Z0=THE SPANWISE LOCATION OF THE PROBE TIP
460   REM Y3=THE YAW ANGLE OF THE FLOW
470   REM
480   REM A1=AMBIENT PRESSURE
490   REM T4=ABSOLUTE AMBIENT TEMP(KELVIN)
500   REM R1=DENSITY (KG/M^3)
510   REM V9=VELOCITY OF THE FREESTREAM
520   REM
```

```
530 DIM Y(1000),Z(1000),M1(1000),M2(1000)
540 DIM P1(1000),P8(1000)
550 REM
560 REM
570 INPUT "ENTER DATE,(MMDDYY)",N8
580 INPUT "ENTER TIME,(HHMM)",N9
590 PRINTER IS 701
600 PRINT "DATE OF RUN IS",N8
610 PRINT "TIME OF RUN IS",N9
620 REM
630 INPUT "ENTER PTS SPANWISE",M3
640 INPUT "ENTER PTS VERTICAL",N3
650 REM N3 MUST BE AN EVEN INTEGER
660 INPUT "ENTER SPANWISE RESOLUTION(IN)",Z4
670 INPUT "ENTER VERTICAL RESOLUTION(IN)",Y4
680 INPUT "INITIAL Z(IN)",Z3
690 INPUT "INITIAL Y(IN)",Y3
700 PRINT "PTS SPANWISE",M3
710 PRINT "PTS VERTICAL",N3
720 PRINT "SPANWISE RESOLUTION (IN)",Z4
730 PRINT "VERTICAL RESOLUTION (IN)",Y4
740 PRINT "INITIAL Z(IN)",Z3
750 PRINT "INITIAL Y(IN)",Y3
760 REM
770 Z(1)=Z3
780 Y(1)=Y3
790 N9=N3/2
800 FOR I7=1 TO N9
810 I6=I7-1
820 J1=2*I6*M3+2
830 J2=2*I6*M3+M3
840 FOR K=J1 TO J2
850 Z(K)=Z(K-1)+Z4
860 Y(K)=Y(K-1)
870 NEXT K
880 J3=2*I6*M3+M3+1
890 Z(J3)=Z(J3-1)
900 Y(J3)=Y(J3-1)+Y4
910 J4=J3+1
920 J5=2*I6*M3+2*M3
930 FOR K=J4 TO J5
940 Z(K)=Z(K-1)-Z4
950 Y(K)=Y(K-1)
960 NEXT K
961 IF I7=N9 THEN 1010
970 J6=J5+1
980 Z(J6)=Z(J6-1)
990 Y(J6)=Y(J6-1)+Y4
1000 NEXT I7
1010 REM
```

```
1030  ASSIGN @Path2 TO "PRS2"
1031  INPUT "DO YOU WANT TO SKIP PRELIMINARY",N$
1032  IF N$="Y" THEN 2290
1040  REM
1050  REM THIS SECTION COMPUTES THE ZERO OFFSET CORRECTION
1060  REM FOR THE TRANSDUCERS.
1070  REM
1080  PRINTER IS 1
1090  PRINT "COMPUTE THE ZERO OFFSET CORRECTION"
1100  PRINT "!!! DISCONNECT ALL TUBING TO THE TRANSDUCERS!!!"
1110  PRINT " HIT CONTINUE WHEN READY"
1120  PAUSE
1130  FOR I=200 TO 204
1140  G2=0
1150  FOR J=1 TO 50
1160  OUTPUT 709;"AI";I;"VT1"
1170  ENTER 709;X2
1180  G2=G2+X2
1190  NEXT J
1200  G3=G2/50
1210  G4(I-199)=G3
1220  NEXT I
1230  REM END OF LOOP FOR ZERO CORRECTION OF TRANSDUCERS
1240  REM
1250  REM THIS LOOP CALIBRATES THE TRANSDUCER AGAINST THE MANOMETER
1260  REM
1270  FOR I=200 TO 204
1280  I1=I-199
1290  PRINT " TRANSDUCER CALIBRATION, ENTER THE MANOMETER PRESSURE IN INCHES OF
              WATER"
1300  PRINT
1310  PRINT
1320  PRINT "ENTER THE PRESSURE FOR TRANSDUCER NR.",I1
1330  INPUT H2
1340  G0=0
1350  FOR J=1 TO 50
1360  OUTPUT 709;"AI";I;"VT1"
1370  ENTER 709;X
1380  G0=G0+X
1390  NEXT J
1400  E1=G0/50
1410  A(I-199)=H2/(E1-G4(I-199))
1420  PRINTER IS 701
1430  PRINT "A",I,"=",A(I-199)
1431  PRINTER IS 1
1432  PRINT "A",I,"=",A(I-199)
1440  INPUT "IS A(I-199) SATISFACTORY (Y/N)",N$
1450  IF N$="N" THEN 1290
1460  PRINT
1470  PRINT
1490  NEXT I
```

```
1500  REM END OF LOOP FOR CALIBRATING TRANSDUCERS
1510  REM
1520  REM ENTER THE VALUES OF STATIC AND TOTAL PRESSURE OF THE FREESTREAM
1530  PRINT "INPUT STATIC PRESSURE OF FREESTREAM (IN.H2O)"
1540  PRINT "USE TRANSDUCER NR.1 AND CHANNEL NR.200"
1550  PRINT
1560  PRINT "HIT CONTINUE WHEN P STATIC IS PROPERLY SET UP"
1570  PAUSE
1580  B6=0
1590  FOR J=1 TO 50
1600  OUTPUT 709;"AI";200;"VT1"
1610  ENTER 709;X6
1620  B6=B6+X6
1630  NEXT J
1640  REM END LOOP FOR ACQUIRING STATIC PRESS.OF FREESTREAM
1650  P9=B6/50
1660  PRINT
1670  PRINT
1680  REM
1690  PRINT "INPUT TOTAL PRESSURE OF THE FREESTREAM,(IN.H2O)"
1700  PRINT "USE TRANSDUCER NR.1 AND CHANNEL NR.200"
1710  PRINT "HIT CONTINUE WHEN P TOTAL PROPERLY SETUP"
1720  PAUSE
1730  B7=0
1740  FOR J=1 TO 50
1750  OUTPUT 709;"AI";200;"VT1"
1760  ENTER 709;X7
1770  B7=B7+X7
1780  NEXT J
1790  REM END OF LOOP FOR ACQUIRING TOTAL PRESSURE OF FREESTREAM
1800  P7=B7/50
1810  REM
1820  REM ENTER AMBIENT CONDITIONS
1830  INPUT "ENTER PAMB (IN.OF HG)",A1
1840  REM
1850  REM LOOP FOR ACQUIRING TEMP OF FREESTREAM VIA THERMOCOUPLE
1860  T=0
1870  FOR J=1 TO 50
1880  OUTPUT 709;"AI";109;"VT1"
1890  ENTER 709;T1
1900  T=T+T1
1910  NEXT J
1920  REM END OF LOOP
1930  T2=T/50
1940  REM CONVERT VOLTAGE TO TEMPERATURE
1950  E1=T2*1000
1960  T3=26.573*E1-1.936679*E1^2+.09725*E1^3-.001277*E1^4
1970  REM
1980  REM CONVERSION TO SI UNIT.
1990  T4=T3+273.15
2000  A1=A1*3386.38
```

```
2010  R1=A1/(287*T4)
2020  C=(P7-P9)*248.7
2030  REM FREESTREAM VELOCITY
2040  U9=(2*C/R1)^.5
2050  REM
2060  REM BEFORE EACH DATA RUN ENSURE THAT P2=P3 I.E. THE PROBE IS BALANCED
2070  PRINT "BALANCE P2 AND P3. "
2080  PRINT "HIT CONTINUE WHEN ALL TUBING HAS BEEN CONNECTED"
2090  PAUSE
2100  REM LOOP FOR BALANCING PROBE
2110  FOR I=201 TO 202
2120  G1=0
2130  FOR J=1 TO 50
2140  OUTPUT 709;"AI";I;"VT1"
2150  ENTER 709;X
2160  G1=G1+X
2170  NEXT J
2180  X=G1/50
2190  E(I-199)=X
2200  P(I-199)=A(I-199)*E(I-199)-G4(I-199)
2210  NEXT I
2220  PRINT
2230  PRINT
2240  PRINT "P2=",P(2)
2250  PRINT "P3=",P(3)
2260  INPUT "DOES P2=P3 (Y/N)",N$
2270  IF N$="N" THEN 2100
2280  REM
2290  REM ENTER THE LOOP FOR ACQUIRING EACH PRESSURE COMPUTING COEFFICENTS
2300  REM AND COMPUTING TWO PRESSURE COEFFICIENTS AND TWO PRESSURES
2301  PRINTER IS 701
2302  PRINT "Y      Z        M1        M2         P1        PAVG"
2303  PRINTER IS 1
2310  REM
2320  K9=0
2321  K2=M3*N3
2330  FOR K=1 TO K2
2331  K9=K
2340  REM
2390  WAIT 10
2400  REM LOOP FOR ACQUIRING EACH PRESSURE
2410  FOR I=200 TO 204
2420  G1=0
2430  REM
2440  FOR J=1 TO 10     !ENTER THE DAS AND SAMPLE EACH PRESSURE 10 TIMES
2450  OUTPUT 709;"AI";I;"VT1"
2460  ENTER 709;X
2470  G1=G1+X
2480  NEXT J
2490  REM
2500  X=G1/10           !AVERAGE THE VALUES
```

```
2510  E(I-199)=X
2520  P(I-199)=A(I-199)*E(I-199)-B(I-199) !CORRECTION FOR ZERO AND TRANS. CAL
2521  IF I=200 THEN
2522      P1(K)=P(I-199)
2523  END IF
2530  NEXT I
2540  REM END OF LOOP FOR ACQUIRING PRESSURES
2550  REM
2560  REM COMPUTE THE AVERAGE OF P2,P3,P4,P5
2570  D5=0
2580  FOR I=2 TO 5
2590  D5=P(I)+D5
2600  NEXT I
2610  P5(K)=D5/4
2620  REM END LOOP
2630  REM
2640  REM COMPUTE THE COEFFICIENTS OF YAW AND PITCH
2650  REM
2651  D1=P(2)-P(3)
2660  D2=P(4)-P(5)
2700  D3=P(1)-P5(K)
2710  M1(K)=D1/D3        ! LOCAL YAW COEFFICENT
2720  M2(K)=D2/D3        !LOCAL PITCH COEFFICENT
2730  PRINTER IS 701
2740  PRINT USING 2750;Y(K),Z(K),M1(K),M2(K),P1(K),P5(K)
2750  IMAGE MDD.DD,2X,MDD.DD,2X,MDD.DDDD,2X,MDD.DDDD,2X,MDD.DDDD,2X,MDD.DDDD
2760  REM
2770  NEXT K
2780  REM
2790  FOR I=1 TO K9
2800  OUTPUT @Path2;Y(I),Z(I),M1(I),M2(I),P1(I),P5(I)
2810  NEXT I
2820  ASSIGN @Path1 TO *
2830  ASSIGN @Path2 TO *
2840  PRINT "**************************************************"
2850  PRINT
2860  PRINT "VELOCITY COMPUTATION AND VELOCITY COMPONENTS"
2870  PRINT
2880  PRINT
2890  PRINT "DATE OF RUN IS",N8
2900  PRINT "TIME OF RUN IS",N9
2910  PRINT
2920  PRINT "DENSITY(KG/M^3)",R1
2930  PRINT "FREESTREAM VELOCITY (M/S)",U9
2940  PRINT "PAMBIENT(N/M^2)",A1
2950  PRINT "TAMBIENT(C)",T3
2960  END
```

```
10   REM PROGRAM VEL
20   REM THIS PROGRAM COMPUTES THE COMPONENTS OF VELOCITY FROM
30   REM THE RAW DATA COLLECTED VIA THE PROGRAM PRS
40   REM
50   REM AUTHOR DAVE EVANS, JANUARY/FEBRUARY, 19
60   REM
70   REM VARIABLE NAMES
80   REM
90   REM P5=AVERAGE PRESSURE
100  REM
110  REM M1=MEASURED YAW COEFFICIENT
120  REM M2=MEASURED PITCH COEFFICIENT
130  REM M3=MEASURED TOTAL COEFFICIENT
140  REM M4=MEASURED STATIC COEFFICIENT
150  REM
160  REM V=THE TOTAL VELOCITY AT THE PROBE TIP
170  REM V1=THE X COMPONENT OF VELOCITY
180  REM V2=THE Y COMPONENT OF VELOCITY
190  REM V3=THE Z COMPONENT OF VELOCITY
200  REM
210  REM X1=THE PITCH ANGLE FROM THE CALIBRATION DATA
220  REM Y=THE YAW ANGLE FROM THE CALIBRATION DATA
230  REM
240  REM X4=THE PITCH ANGLE OF THE FLOW
250  REM
260  REM Y=THE VERTICAL LOCATION  OF THE PROBE TIP
270  REM Z=THE SPANWISE LOCATION OF THE PROBE TIP
280  REM Y3=THE YAW ANGLE OF THE FLOW
290  REM
300  DIM C1(77),C2(77),C3(77),C4(77),M1(800),M2(800)
310  DIM X1(77),Y(77),Y1(800),P1(800),P6(800),P9(800)
320  DIM Z0(800),V(800),V1(800),V2(800),V3(800)
330  DIM Z(800),F(800),V4(800),V5(800),V6(800),V7(800)
340  REM
350  INPUT "WHAT IS THE DENSITY FOR THIS RUN(KG/M^3)",R1
360  REM
370  REM READ CALIBRATION DATA INTO COMPUTER MEMORY
380  REM
390  ASSIGN @Path1 TO "CAL"
400  FOR I=1 TO 77
410  ENTER @Path1;X1(I),Y(I),C1(I),C2(I),C3(I),C4(I)
420  NEXT I
430  REM READ RAW DATA INTO COMPUTER MEMORY
440  ASSIGN @Path2 TO "PRS2"
450  FOR I=1 TO 800
460  ENTER @Path2;Y1(I),Z(I),M1(I),M2(I),P1(I),P6(I)
470  NEXT I
480  REM
490  CREATE BDAT "VEL2",225
500  ASSIGN @Path3 TO "VEL2"
```

```
510  FOR K=1 TO 400
520  K9=K
530  Y1(K)=Y1(K)*2.54
540  Z(K)=Z(K)*2.54
550  REM
560  REM COMPUTE THE FIRST APPROXIMATION OF YAW ANGLE
570  B3=-.15809924
580  B4=-7.25566712        ! COEFFICENTS AND POLYNOMIAL ARE
590  C5=.10583669          ! FROM FORTRAN PROGRAM ... AND
600  C6=.004015636         ! ARE COMPUTED FROM THE ... YAW ...
610  C7=.009000069         ! YAW DATA FROM THE CALIBRATION
620  C8=-.03009867
630  Y3=B3+B4*M1(K)+C5*M1(K)^2+C6*M1(K)^3+C7*M1(K)^4+C8*M1(K)^5
640  REM
650  REM GO TO THE SUB-ROUTINE FOR PITCH ANGLE INTERPOLATION
660  GOSUB 1400
670  REM
680  REM GO TO THE SUB-ROUTINE FOR YAW ANGLE INTERPOLATION
690  GOSUB 1000
700  REM
710  REM GO TO THE SUB-ROUTINE FOR CP TOTAL AND CP STATIC INTERPOLATION
720  GOSUB 1350
730  REM
740  REM THIS SECTION COMPUTES THE MAGNITUDE OF THE LOCAL VELOCITY
750  REM VECTOR AT THE PROBE TIP
760  REM
770  P1(K)=P1(K)*248.8     !CONVERT P1 TO N/M^2
780  P6(K)=P6(K)*248.8     !CONVERT P(6) TO N/M^2
790  REM CALCULATE STATIC AND TOTAL PRESSURE
800  P8=P6(K)-M4*(P1(K)-P6(K))
810  P8=-P8     !DONE BECAUSE INTERPOLATION RESULTS IN NEGATIVE VALUE FOR PSTAT
820  P(K)=P1(K)-M3*(P1(K)-P6(K))
830  V4(K)=(2/R1*(P(K)-P8))^.5
840  REM
850  REM COMPUTE THE COMPONENTS OF VELOCITY
860  DEG
870  V5(K)=V4(K)*COS(X4)*COS(Y3)
880  V6(K)=V4(K)*SIN(X4)
890  V7(K)=V4(K)*COS(X4)*SIN(Y3)
900  NEXT K
910  REM END OF DATA REDUCTION LOOP
920  REM RE-ORDER DATA
930  I1=1
940  I2=40
950  FOR I=1 TO 721 STEP 80
960  J1=I1
970  J2=I2
980  FOR K=1 TO 40
990  Z0(J1)=Z(J2)
1000 P3(J1)=P(J2)
1010 V(J1)=V4(J2)
```

```
1020  V1(J1)=V5(J2)
1030  V2(J1)=V6(J2)
1040  V3(J1)=V7(J2)
1050  J1=J1+1
1060  J2=J2-1
1070  NEXT K
1080  I1=I1+30
1090  I2=I2+40
1100  NEXT I
1110  I3=41
1120  FOR I=41 TO 803 STEP 50
1130  K=I3
1140  FOR J=1 TO 40
1150  Z0(K)=Z(K)
1160  P9(K)=P(K)
1170  V(K)=V4(K)
1180  V1(K)=V5(K)
1190  V2(K)=V6(K)
1200  V3(K)=V7(K)
1210  K=K+1
1220  NEXT J
1230  I3=I3+60
1240  NEXT I
1250  FOR K=1 TO K9
1260  OUTPUT @Path3;Y1(K),Z0(K),P9(K),[illegible]
1270  NEXT K
1280  ASSIGN @Path1 TO *
1290  ASSIGN @Path2 TO *
1300  ASSIGN @Path3 TO *
1310  PRINTER IS 1
1320  PRINT "Y(CM)      Z(CM)      P[illegible]      [illegible]      VX(M/S)      VY(M/S)
 VZ(M/S)"
1330  FOR I=1 TO K9
1340  PRINT USING 1350;Y1(I),Z0(I),P9(I),[illegible]
1350  IMAGE MDD.DD,2X,MDD.DD,2X,MDDD.DDD,2X,MDD.DDD,2X,MDD.DDD,2X,MDD.DDD,2X,M
.DDD
1360  NEXT I
1370  REM
1380  STOP
1390  REM
1400  REM PITCH ANGLE INTERPOLATION
1410  REM
1420  FOR I=1 TO 77
1430  IF Y3<Y(I) THEN 1450     !SEARCH THRU CALIBRATION DATA TO FIND
1440  NEXT I                   !YAW ANGLES WHICH BRACKET THE APPROX YAW
1450  K1=I                     !ANGLE
1460  K2=I-7
1470  K3=I-1
1480  K4=I+5
1490  FOR J=K2 TO K3              !FIND THE PITCH ANGLE WHICH CORRESPONDS TO
1500  IF M2 K [illegible](J) THEN [illegible]     !THE MEASURED PITCH COEFF.
```

```
1510  NEXT J
1520  Z1=(C2(J)-M1(K))/(C2(J)-C2(J-1))
1530  X2=X1(J)-Z1*(X1(J)-X1(J-1))          'BRACKETING [illegible]
1540  FOR J=F1 TO F4
1550  IF M2(K) [illegible] C2(J) THEN 15[illegible]0
1560  NEXT J
1570  Z2=(C2(J)-M2(K))/(C2(J)-C2(J-1))
1580  [illegible]=X1(J)-Z2*(X1(J)-X1(J-1))          'BRACKETING PITCH [illegible]
1590  [illegible]=Y(F4)-Z[illegible]*(Y(F4)-Y(F3))
1600  [illegible]=Y[illegible]-Z2*(Y3-Y2)          'PITCH [illegible]
1610  RETURN
1620  REM
1630  REM Y-W ANGLE INTERPOLATION
1640  REM
1650  FOR I=1 TO [illegible]7
1660  IF [illegible] I THEN 1690
1670  NEXT I
1680  [illegible]=I-[illegible]
1690  [illegible]=I-1
1700  FOR J=H2 TO H3                   'FIND YAW ANGLES WHICH
1710  IF [illegible]4 X1(J) THEN 1730     'CORRESPOND TO THE MEASURED
1720  NEXT J                            'OR YAW ON PITCH ANGLES WHICH
1730  F1=J                              'BRACKET X4
1740  F2=J-1
1750  F3=J+6
1760  F4=J+7
1770  Z4=(C1(F1)-M1(K))/(C1(F1)-C1(F4))
1780  Y4=Y(F1)-Z4*(Y(F1)-Y(F4))
1790  Z5=(C1(F2)-M1(K))/(C1(F2)-C1(F3))
1800  Y5=Y(F2)-Z5*(Y(F2)-Y(F3))
1810  Z6=(X1(F1)-X4)/(X1(F1)-X1(F2))
1820  Y3=Y4-Z6*(Y4-Y5)
1830  RETURN
1840  REM
1850  REM INTERPOLATION FOR LOCAL COEFFFICIENTS OF STATIC AND TOTAL PRESSURE
1860  ZZ=0
1870  ZZ=0
1880  FOR I=1 TO 77
1890  IF Y3 Y(I) THEN 1910
1900  NEXT I
1910  F1=I
1920  F2=I-7
1930  F3=I-1
1940  F4=I+5
1950  FOR J=F2 TO F3
1960  IF X4 X1(J) THEN 1980
1970  NEXT J
1980  F5=J
1990  F6=J-1
2000  F7=J+[illegible]
```

```
2010  F8=J+6
2020  Z3=(Y1(F6)-X4)/(Y1(F6)-Y1(F5))
2030  N4=C4(F6)-Z3*(C4(F6)-C4(F5))
2040  N3=C3(F6)-Z3*(C3(F6)-C3(F5))
2050  L4=C4(F8)-Z3*(C4(F8)-C4(F7))
2060  L3=C3(F8)-Z3*(C3(F8)-C3(F7))
2070  Z2=(Y(F6)-Y3)/(Y(F6)-Y(F8))
2080  M4=N4-Z2*(N4-L4)         ! LOCAL STATIC COEFFICIENT
2090  M3=N3-Z2*(N3-L3)         ! LOCAL TOTAL COEFFICIENT
2100  RETURN
2110  STOP
2120  END
```

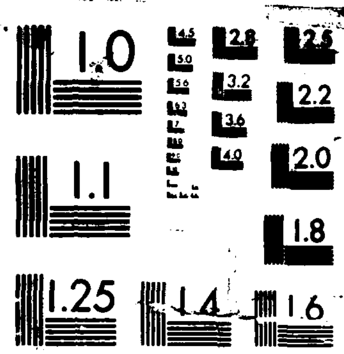
```
1     REM PROGRAM PLOT
2     REM THIS PROGRAM MAKES CONTOUR PLOTS FOR STREAMWISE
3     REM VELOCITY AND CAN BE MODIFIED TO MAKE CONTOURS [illegible]
4     REM FOR TOTAL PRESSURE
10    DIM [illegible]
20    DIM X(300)
30    ASSIGN @Path1 TO "VEL[illegible]"
40    FOR I=1 TO 300
50    ENTER @Path1;[illegible]
60    NEXT I
70    [illegible]
80    [illegible]
90    FOR I=2 TO 300
100   IF [illegible] THEN [illegible]
110   IF [illegible] THEN [illegible]
120   NEXT I
130   [illegible]
140   FOR I=1 TO 300
150   [illegible]
160   IF [illegible] THEN [illegible]
170   FOR J=1 TO 9
180   Z1=V8+(J-1)*D
190   Z2=V8+J*D
200   IF V1(I)>Z1 AND V1(I)<Z2 THEN X(I)=J
210   NEXT J
220   NEXT I
221   FOR I=1 TO 300
222   IF X(I)<9 THEN GOTO 226
223   Z1=V8+(10*D)
224   Z2=V5+(9.7*D)
225   IF V1(I)>Z1 AND V1(I)<Z2 THEN X(I)=0
226   NEXT I
230   GINIT
240   !PLOTTER IS 705,"HPGL"
250   PLOTTER IS CRT,"INTERNAL"
260   GRAPHICS ON
270   CSIZE 4.5,.65
280   MOVE 39,10
290   LABEL "EMBEDDED VORTEX 20 M/S "
300   MOVE 43.5,7
301   LABEL "75% FILM COOLING"
302   MOVE 41,85
310   LABEL "STREAMWISE VELOCITY"
320   MOVE 56.17
321   CSIZE 3.0
330   LABEL "Z  CM "
340   MOVE 5.56
341   CSIZE 3.0
350   Label$="Y  CM "
360   FOR I=1 TO 6
370   [illegible]
```

```
380    NEXT I
390    VIEWPORT 15,114,[illegible]
400    SHOW -16.6,0,11
410    FRAME
420    AXES .5,.5,0,0,[illegible]
430    AXES .5,.5,-16,12,[illegible]
440    AXES .5,.5,6,12,[illegible]
441    CSIZE 2.0,.65
442    MOVE -14.7,10.55
444    LABEL "VELOCITY RANGES"
445    A=10.1
446    FOR K=0 TO 9
447    B=A-K*.35
448    MOVE -14.3,B
449    I2=V8+K*D
450    I1=V8+(K+1)*D
451    IF K=9 THEN I1=V8+K*D+.7*D
452    LABEL USING "D,2X,DD.D,X,DD.D";K,I2,I1
453    NEXT K
454    MOVE -14.3,B-.35
455    LABEL USING "D,2X,DD.D,X,DD.D";0,I1,V9
456    CSIZE 1.3,.72
457    FOR I=1 TO 600
458    MOVE Z0(I),Y1(I)
459    IF Y1(I)>5.0 AND Z0(I)>-10. THEN GOTO 461
460    LABEL USING "D";X(I)
461    NEXT I
462    CLIP OFF
463    CSIZE 2.0,.55
470    FOR I=-.2 TO 11.8 STEP 2
480      MOVE -17.5,I
490      I1=I+.2
500      LABEL USING "#,DD.D";I1
510    NEXT I
520    FOR J=-17.0 TO 5.0 STEP 2
530       MOVE J,-.7
540       J1=J+1.0
550       LABEL USING "#,MDD.D";J1
560    NEXT J
570    END
```

```
10    REM PROGRAM VECTOR
20    REM THIS PROGRAM USE DATA FROM VELO DATA FILES
30    REM TO PLOT SECONDARY FLOW VECTORS
40    DIM Y1(800),Z0(800),P9(800 [illegible]
50    DIM X(800),Y(5),Z(5)
60    ASSIGN @Path1 TO "VELOIA"
70    FOR I=1 TO 800
80    ENTER @Path1;Y1(I),Z0(I),P9(I),[illegible]
90    NEXT I
100   GINIT
110   PLOTTER IS 705,"HPGL"
120   !PLOTTER IS CRT,"INTERNAL"
130   GRAPHICS ON
140   CSIZE 4.5,.65
150   MOVE 38,10
160   LABEL "EMBEDDED [illegible]"
170   MOVE 43.5,7
180   LABEL "75% FILM [illegible]"
190   MOVE 35.4,85
200   LABEL "SECONDARY FLOW [illegible]"
210   MOVE 62,17
220   CSIZE 3.0
230   LABEL "Z  CM "
240   MOVE 5,65
250   CSIZE 3.0
260   Label$="Y  CM "
270   FOR I=1 TO 6
280     LABEL Label$[I,I]
290     NEXT I
300   VIEWPORT 15,114,25,[illegible]
310   SHOW -15.5,0,12
320   FRAME
330   AXES .5,.5,0,0,2,2
340   AXES .5,.5,-15,12,2,2
350   AXES .5,.5,6,12,2,2
360   CSIZE 1.3,.72
370   S1=.21
380   A1=0.
390   FOR K=751 TO 800
400   A1=A1+V1(K)
410   NEXT K
420   A1=A1*S1/40.
430   MOVE -14.5,10.6
440   Y(1)=10.6
450   Y(2)=10.6
460   Z(1)=-14.5
470   Z(2)=-14.5+A1*.1
480   FOR J=1 TO 2
490   PLOT Z(J),Y(J)
500   NEXT J
510   PENUP
```

AD-A183 420 STUDY OF VORTICES EMBEDDED IN BOUNDARY LAYERS WITH FILM 2/2
COOLING(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
D L EVANS MAR 87 MIPR-FY-1455-86-N0616

UNCLASSIFIED F/G 20/4 NL



MICROCOPY RESOLUTION TEST CHART

```
520  MOVE -15.,9.5
530  CSIZE 2.0,.65
540  LABEL "0.1 FS VELOCITY"
550  FOR I=1 TO 900
560  Y(1)=Y1(I)
570  Z(1)=Z0(I)
580  Y(2)=Y1(I)+S1*V2(I)
590  Z(2)=Z0(I)+S1*V3(I)
600  !
610  ! BUSINESS TO MAKE ARROWS
620  !
630  D1=(Y(2)-Y(1))
640  D2=(Z(2)-Z(1))
650  DEG
660  A3=ATN(D2/D1)
670  A4=45-A3
680  E3=0.
690  IF D1<0 AND D2>0 THEN E3=1.0
700  IF E3=1.0 AND A3>-45. THEN A4=A3+135
710  D4=((Z(2)-Z(1))^2+(Y(2)-Y(1))^2)^.5
720  D4=.20*D4
730  D8=1.0
740  D9=1.0
750  IF A4<45 THEN D9=-1.0
760  E1=0.
770  E2=0.
780  IF D1>0 AND D2<0 THEN D9=-1.0
790  IF D1>0 AND D2<0 THEN D8=-1.0
800  IF D1<0 AND D2<0 THEN D8=-1.0
810  IF D1<0 AND D2<0 THEN D9=-1.0
820  IF D1<0 AND D2>0 THEN D8=-1.0
830  IF D1<0 AND A3>45 THEN D8=1.0
840  IF A3>-45. AND A3<0. THEN D8=1.0
850  IF D1>0 AND D2<0 THEN E1=1.0
860  IF E1=1.0 AND A3<-45. THEN D8=1.0
870  IF D1<0 AND D2<0 THEN E2=1.0
880  IF E2=1.0 AND A3<45. THEN D9=1.0
890  Y(3)=Y(2)-D4*COS(A4)*D8
900  Z(3)=Z(2)-D4*SIN(A4)*D9
910  Y(4)=Y(2)
920  Z(4)=Z(2)
930  A5=A4-90
940  IF D1>0 AND D2<0 THEN D8=1.0
950  IF D1<0 AND D2<0 THEN D9=1.0
960  Y(5)=Y(2)+D4*COS(A5)*D9
970  Z(5)=Z(2)+D4*SIN(A5)*D8
980  !
990  ! END OF BUSINESS TO MAKE ARROWS
1000 !
1010 MOVE Z0(I),Y1(I)
```

```
1020  IF Y1(I)>8.5 AND Z0(I)<-10. THEN GOTO 1070
1030  FOR J=1 TO 5
1040  PLOT Z(J),Y(J)
1050  NEXT J
1060  PENUP
1070  NEXT I
1080  CLIP OFF
1090  CSIZE 2.0,.55
1100  FOR I=-.2 TO 11.8 STEP 2
1110    MOVE -17.5,I
1120    I1=I+.2
1130    LABEL USING "#,DD.D";I1
1140  NEXT I
1150  FOR J=-17.0 TO 5.0 STEP 2
1160     MOVE J,-.7
1170     J1=J+1.0
1180     LABEL USING "#,MDD.D";J1
1190  NEXT J
1200  END
```

APPENDIX C
UNCERTAINTY ANALYSIS

Uncertainty analysis was performed using the method originally attributed to Kline and McCormick,. [Ref. 13]. Let δ_r be the uncertainty in the result and δ_1, δ_2, . . ., δ_n be the uncertainties associated with each independent variable. The uncertainty in the result can be expressed as

$$\delta_r = [\sum((\partial R/\partial x_i) \times (\delta_i))]^{1/2} \qquad \text{(eqn C.1)}$$

To determine the uncertainty of the pitch angle, α, a straight line approximation was made for α

$$\alpha = m + b(Cp_{pitch}) \qquad \text{(eqn C.2)}$$

The following independent variables were determined: $\delta_m = \pm 1.97°$, $\delta_b = \pm 2.32°$, and $\delta_b = \pm 0.04637$. The uncertainty of α, was determined to be $\pm$ 2.36°. The high uncertainy of the pitch angle is caused by the probe being highly sensitive in the pitch plane.

The uncertainty of the yaw angle,β, is determined in a similar manner. Once again, a straight line approximation is made.

$$\beta = m + b(Cp_{yaw}) \qquad \text{(eqn C.3)}$$

In this case, the uncertainties of the independent variables were found to be $\delta_m = \pm 0.954$, $\delta_b = 0.5924$, and $\delta_{Cp_{yaw}} = \pm 0.058$. From these values the uncertainty of β was calculated to be $\pm$ 1.29 °

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