# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

# THESIS

FLOW FIELD MEASUREMENTS OF AN AIRFOIL
WITH A DEFLECTED SPOILER USING
A TWO-COMPONENT LDV SYSTEM

by

Michael J. Foreman

September 1986

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# REPORT DOCUMENTATION PAGE

| 1a REPORT SECURITY CLASSIFICATION<br><br>UNCLASSIFIED | 1b RESTRICTIVE MARKINGS |
|---|---|
| 2a SECURITY CLASSIFICATION AUTHORITY | 3 DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; |
| 2b DECLASSIFICATION/DOWNGRADING SCHEDULE | distribution is unlimited. |

| 4 PERFORMING ORGANIZATION REPORT NUMBER(S) | 5 MONITORING ORGANIZATION REPORT NUMBER(S) |
|---|---|
| | |

| 6a NAME OF PERFORMING ORGANIZATION<br>Naval Postgraduate School | 6b OFFICE SYMBOL<br>(If applicable)<br>Code 31 | 7a NAME OF MONITORING ORGANIZATION<br>Naval Postgraduate School |
|---|---|---|
| 6c ADDRESS (City, State, and ZIP Code)<br><br>Monterey, California    93943-5000 | | 7b. ADDRESS (City, State, and ZIP Code)<br><br>Monterey, California    93943-5000 |

| 8a NAME OF FUNDING/SPONSORING<br>ORGANIZATION | 8b OFFICE SYMBOL<br>(If applicable) | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
|---|---|---|

| 8c ADDRESS (City, State, and ZIP Code) | 10 SOURCE OF FUNDING NUMBERS | | | |
|---|---|---|---|---|
| | PROGRAM<br>ELEMENT NO | PROJECT<br>NO | TASK<br>NO | WORK UNIT<br>ACCESSION NO |

11 TITLE (Include Security Classification)

FLOW FIELD MEASUREMENTS OF AN AIRFOIL WITH A DEFLECTED SPOILER USING A TWO-COMPONENT LDV SYSTEM

12 PERSONAL AUTHOR(S)
Foreman, Michael J.

| 13a TYPE OF REPORT<br>Master's Thesis | 13b TIME COVERED<br>FROM _____ TO _____ | 14 DATE OF REPORT (Year, Month, Day)<br>1986 September | 15 PAGE COUNT<br>75 |
|---|---|---|---|

16 SUPPLEMENTARY NOTATION

| 17 | COSATI CODES | | 18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Spoiler, LDV |
| | | | |
| | | | |

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

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The experiment was conducted in the NASA Ames 11 cm x 25 cm indraft tunnel. A two-component LDV system was developed and set up, and measurements were obtained along the upper surface of the airfoil (ahead of and behind the spoiler) as well as in its wake, close to the trailing edge. Mean velocity profiles and turbulent stresses were calculated and comparisons were made with previous hot-wire experiments.

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| 20 DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21 ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED | |
|---|---|---|
| 22a NAME OF RESPONSIBLE INDIVIDUAL<br>Satyanarayana Bodapati | 22b TELEPHONE (Include Area Code)<br>408-646-2491 | 22c OFFICE SYMBOL<br>Code 31 |

DD FORM 1473, 84 MAR    83 APR edition may be used until exhausted    SECURITY CLASSIFICATION OF THIS PAGE
All other editions are obsolete

19. Abstract (cont)
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with a Deflected Spoiler Using
a Two-Component LDV System

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1986

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# TABLE OF CONTENTS

## LIST OF TABLES

7

# LIST OF FIGURES

## ACKNOWLEDGEMENTS

# I. INTRODUCTION

## A.    SPOILERS

A spoiler is a plate on the upper surface of a wing which can be deflected to spoil the flow and to cause early separation. Consequently, lift decreases and drag increases. Spoilers are used as effective aerodynamic control surfaces in transport aircrafts. They can be symmetrically deflected as speed brakes or as lift dumpers at touch down. When spoilers are deflected asymmetrically, they can provide substantial amounts of roll control in certain conditions of flight.

The flow field of an airfoil with a deflected spoiler is complex: including flow separation, reattachment and vortex shedding [Ref. 1:p. 1].

The basic steady state structure of the flow field of an airfoil with a deflected spoiler has been measured and hypothesized by the Boeing Research Group [Ref. 2]. Further work into how the unsteady wake relates to the airfoil geometry and to other parameters was undertaken by Lee, et al. In their experiments, Lee, et al., used hot-wire anemometers and pitot tubes to systematically measure the mean and fluctuating quantities on the airfoil surface, as well as in the wake, in order to better understand the structure of this flow field. [Ref. 1]

## B.    LASER DOPPLER VELOCIMETER SYSTEMS

Advanced research in experimental fluid dynamics requires a familiarity with sophisticated measurement techniques. Optical methods and in particular, the Laser Doppler Velocimeter (LDV) are now recognized as the most reliable means for performing measurements in complex turbulent flows [Ref. 3].

Since its inception in 1964, the LDV technique has been revised, developed, and tested by many researchers and its capabilities are reasonably well-understood. The method has the advantage of performing instantaneous, non-intrusive velocity measurements of small particles suspended in the flow. These measurements are relatively independent of fluid properties and the method does not require frequent calibration. Furthermore, its ability to measure the flow without disturbing it is especially attractive. However, because of the range of disciplines involved including optics, electronics, light scattering, and signal processing, the implementation of this method can be quite onerous. Serious measurement errors can occur if the measurement techniques are not applied correctly.

11

## C.    THESIS GOALS

Considering this previous work, the goals of this thesis experiment were threefold. First, to develop and set up a two-component LDV system with complete computer-experiment integration employed.   Second, to utilize this LDV system to measure the mean and fluctuating velocities of an airfoil with a deflected spoiler flap, especially in the reverse flow region and the near wake where the fluctuations are large. Third, to compare the LDV data obtained with the previous hot-wire anemometry data.

# II. EXPERIMENTAL ASPECTS

## A.    EXPERIMENTAL SETUP

The experiments were conducted in the NASA Ames 11 cm × 25 cm indraft wind tunnel. Figure 2.1 shows the test section of this tunnel. The test section is equipped with slotted walls and a number of plenum chambers above and below the centerline. These features were used in previous experiments to give the tunnel adaptive walls. The adaptive wall concept was not employed in this experiment, however the slotted walls did provide a means of reducing wall interference. The wind tunnel also is equipped with interchangeable glass and plexiglas test section windows. For these experiments, the glass windows were used due to their higher refractive qualities which enhance the LDV signals.

The basic model used was a Boeing advanced transport research airfoil section with a 6-inch chord and maximum thickness ratio of 11.3% as shown in Figure 2.2. This airfoil has a spoiler of 15.5% chord length hinged at 73% chord. The coordinates of the airfoil are given in Table I. This airfoil was selected because of the availability of hot-wire anemometer and pitot tube experimental data for comparison with the two-component LDV results.

## B.    INSTRUMENTATION

### 1. Pressure Instrumentation

For this experiment, pressure information was obtained by taking advantage of a bank of six, 24-port Scanivalves tapped into the tunnel during a previous experiment. The six pressure transducers were of the differential type with a range of ±5 psig. One side of each transducer was connected with the measured pressure through plastic tubing while the other side of each transducer was vented to atmosphere.

In order to calibrate the transducers, one port of each Scanivalve was tapped to a calibration pressure generated by a small electric vacuum pump. Another port of each Scanivalve was tapped to the atmosphere. The calibration pressure and atmospheric pressure were each measured by alternate methods. These two known pressures and the values given for them by each transducer allowed the Scanivalves to be calibrated.
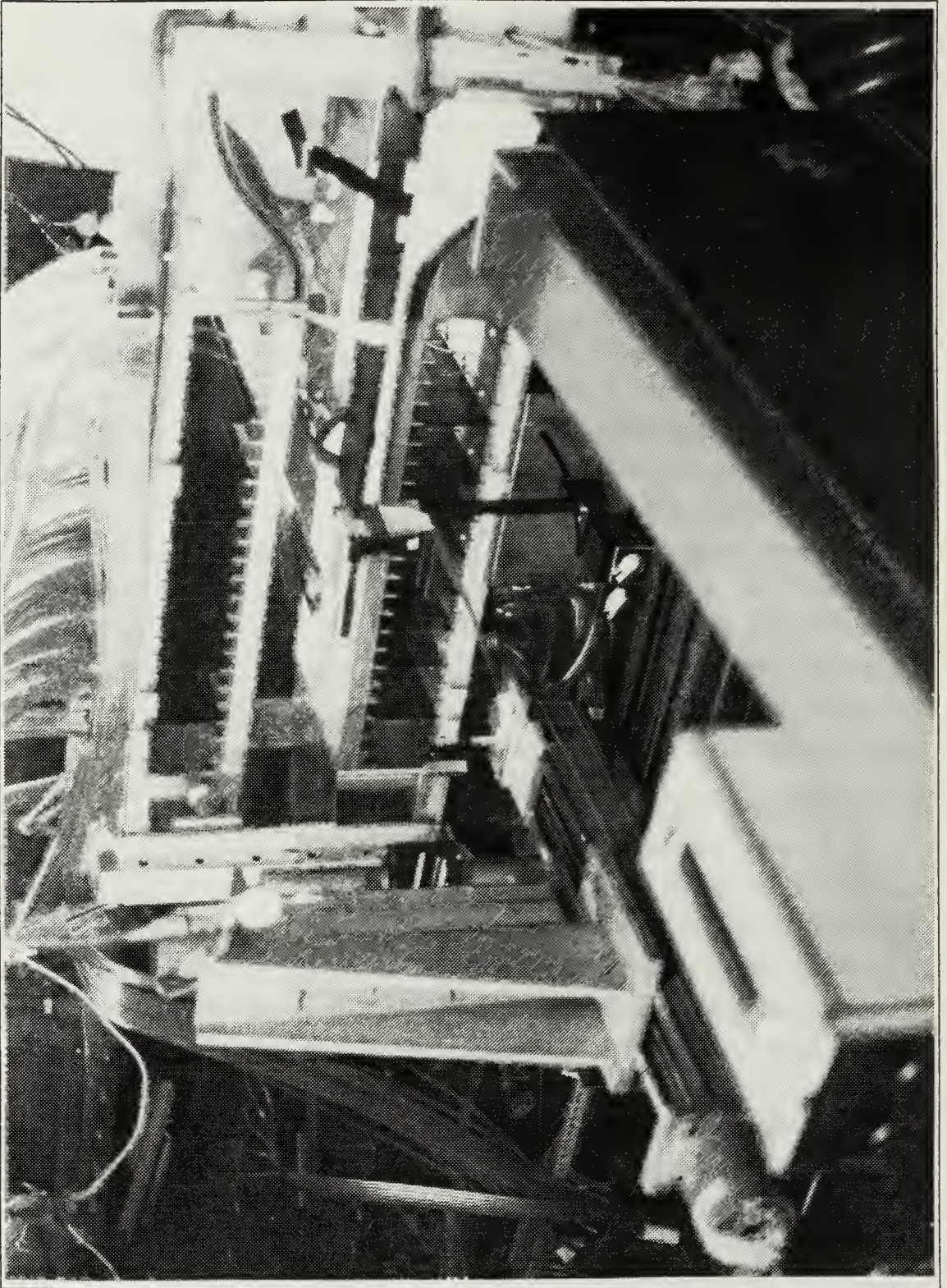
Figure 2.1   NASA Ames indraft wind tunnel test section.

14
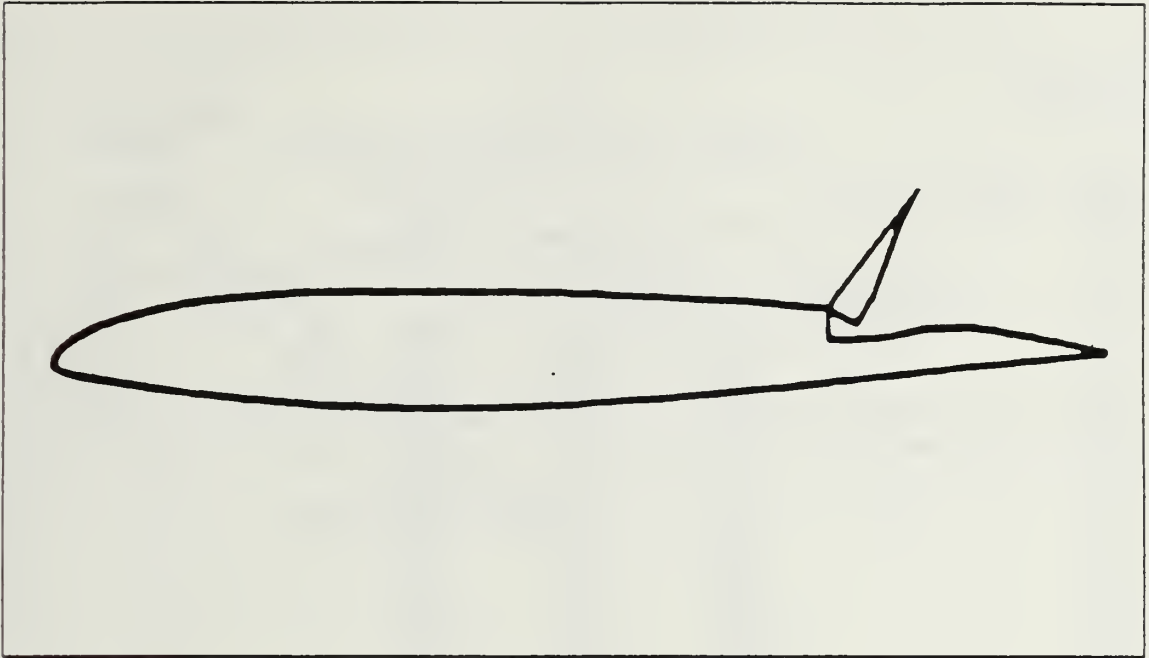
Figure 2.2    Boeing advanced transport research airfoil section.

## 2.  Laser Doppler Velocimeter Instrumentation

Figure 2.3 shows the two-component, two color LDV arrangement used at NASA Ames.  The laser is a four Watt Argon ion unit (Spectra Physics Model 64). This laser is configured with an end cavity multiline reflector which allows it to operate in the multiline mode.  Translation stages in three axes permit positioning of the probe volume anywhere in the test section.

In the multiline mode, the resultant beam is comprised of all wavelengths inherent to the Argon ion unit.  This beam exits the laser in a fairly collimated state, hence an external collimator is not required.  The beam first passes through a half-wave plate (polarization rotator) where it becomes horizontally polarized.  A set of Brewster angle prisms is then used to separate the primary beam into its various wavelengths.  To obtain maximum light transmission through the prisms, the beam polarization must be parallel to the plane defined by the incident and refracted beams [Ref. 4].  This was the reason that the initially vertically-polarized laser beam was passed through a polarization rotator prior to entering the dispersion prism.  When the two prism method is used, the prisms also turn the beams which, with a little planning, may be used to advantage.  At some distance from the prisms, the beams have

15

## TABLE I

## AIRFOIL COORDINATES (INCHES)

| X | $Y_{upper}$ | $Y_{lower}$ |
|---|---|---|
| 0.0 | 0.0 | 0.0 |
| .0030 | .0222 | -.0108 |
| .0060 | .0300 | -.0162 |
| .0150 | .0468 | -.0258 |
| .0300 | .0672 | -.0348 |
| .0900 | .1242 | -.0588 |
| .1200 | .1452 | -.0672 |
| .1500 | .1626 | -.0750 |
| .2250 | .2004 | -.0912 |
| .3000 | .2304 | -.1050 |
| .4500 | .2790 | -.1296 |
| .6000 | .3126 | -.1524 |
| .7500 | .3396 | -.1728 |
| .9000 | .3594 | -.1920 |
| 1.2000 | .3858 | -.2250 |
| 1.5000 | .3990 | -.2502 |
| 1.8000 | .4044 | -.2670 |
| 2.1000 | .4038 | -.2748 |
| 2.4000 | .4002 | -.2742 |
| 2.7000 | .3924 | -.2658 |
| 3.0000 | .3816 | -.2502 |
| 3.3000 | .3678 | -.2298 |
| 3.6000 | .3510 | -.2064 |
| 3.9000 | .3288 | -.1818 |
| 4.2000 | .3018 | -.1560 |
| 4.5000 | .2700 | -.1308 |
| 4.8000 | .2304 | -.1044 |
| 5.1000 | .1842 | -.0792 |
| 5.4000 | .1308 | -.0540 |
| 5.7000 | .0696 | -.0282 |
| 6.0000 | .0024 | -.0024 |

sufficient separation so mirrors can be used to direct the individual beams to the next optical components. The two stronger lines, green (514.5 nm) and blue (488 nm), are guided by means of turning mirrors to Bragg cells. The weaker, unused lines are "trapped" (blocked by nonreflective plates) to keep them from interfering with the system. Prior to reaching its Bragg cell, the green beam is passed through another half-wave plate in order to vertically polarize it.

A Bragg cell is an acousto-optic device. Both the blue and green beams are passed through Bragg cells which split each into two equal-intensity, slightly diverging beams while inducing a 40 MHz modulation in one of the beams in each pair. The difference is that the green beam is split in the vertical plane while the blue beam is split in the horizontal plane (Figure 2.3).
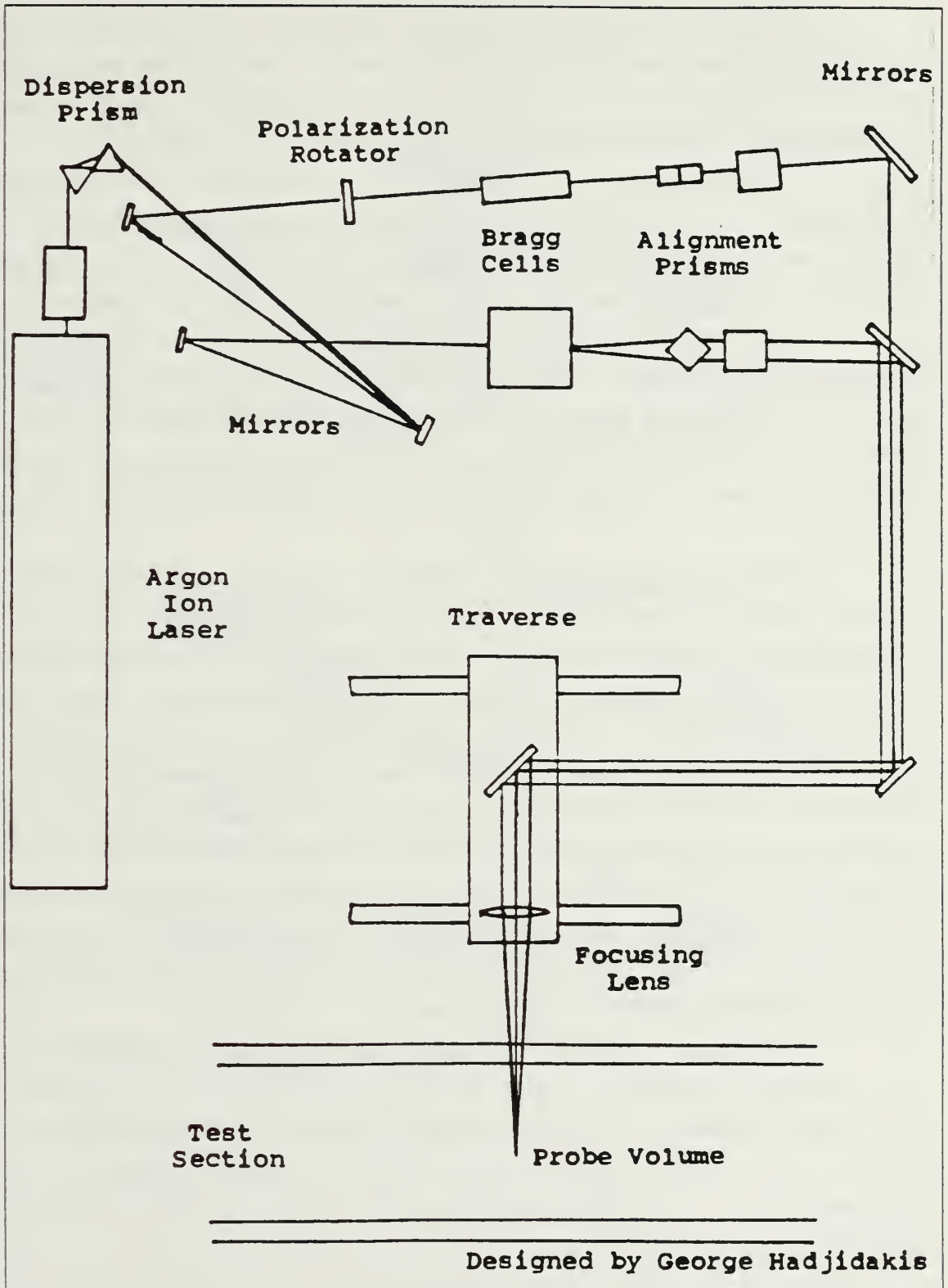
16

Figure 2.3  Two-component LDV arrangement used at NASA Ames.

17

In each case (blue and green), the two diverging beams are then made parallel by passing each pair through its own alignment prism. From there on, turning mirrors guide the beams through the translation stages. They are finally focused by means of a condensing lens at the desired point in the test section of the wind tunnel.

The four beams must all focus to a common point in the flow and be approximately coaxial. Using the steering mirrors for the appropriate beam pair, the focused beams are adjusted to visually overlap. Following this, various techniques exist for making fine adjustments to insure the beams all cross at a common point.

An off-axis, forward scatter configuration has been selected for the receiving optics used at NASA Ames. This gives flexibility to the system so it can be adjusted to different requirements; if maximum signal strength is required, angular deviation from the beam axis of symmetry is minimized. If focusing on the smallest part of the probe volume is of interest, the angular deviation is made as large as the physical constraints will allow.

The first lens in the receiving optics is the aperture through which the scattered light is collected (Figure 2.4). The second lens collimates the beam. A collimated beam is required by the polarization beamsplitter for maximum efficiency. The polarization beamsplitter allows the vertically polarized green beam to pass straight through while the horizontally polarized blue beam is reflected upward. The use of polarization rather than frequency to separate the two wavelengths substantially increases the efficiency of the system. Each beam then passes through a line filter centered on the respective wavelength (blue or green) in order to reduce both the ambient light and the cross-talk due to impure polarization. Each line filter is followed by a lens which serves to focus the light onto the pinhole aperture of the respective photomultiplier. The photomultipliers convert this light energy into electronic signals which are then passed on to the signal processors.

Preamplifiers are located in the photodetector housings to further increase the signal amplitude and drive the signal over relatively long cables. The preamplifier is kept close to the detectors in order to increase the signal level before additional noise enters the signal cables. It is always good practice to amplify the signal as much as possible with the photomultiplier tube before going to the preamplifier which inevitably produces electronic noise.

The signal processors used in this experiment were of the counter type and produced by Macrodyne. These processors have good resolution and superior noise
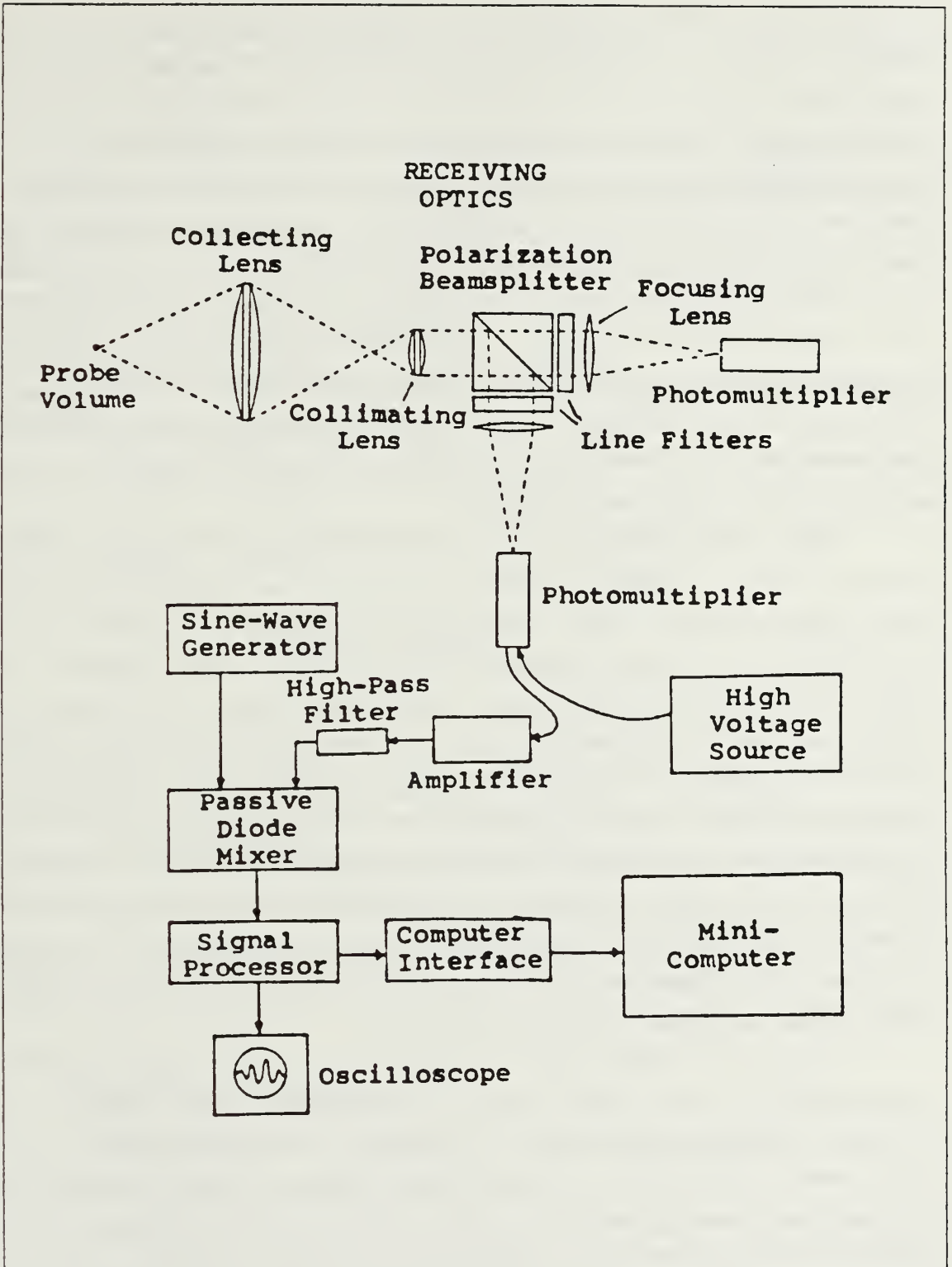
Figure 2.4    Computer-experiment integration.

rejection circuitry. The Macrodyne unit is a high-speed counter with a 1 GHz clock designed to operate in a variety of experimental situations. It has been applied under single particle, multi-particle and multi-velocity conditions. In addition to the basic 5/8 (or 10/16) signal validation criteria and oversize particle rejection, a sophisticated multi-level sequence validation has been incorporated. This allows the experimenter to select the criteria which will best yield data for a given signal-to-noise ratio, signal level, seeding level, Doppler frequency, and fluctuation, indicative of the test situation.

When the particle seeding rate is low, as was the case in this experiment, the LDV signals become intermittent bursts. Under these conditions, the counter processor is the best choice as a means for obtaining the Doppler difference frequency. If the seeding is high, the signals will be almost continuous with random amplitude and phase fluctuations. The counter will still function but cannot be expected to produce accurate results to better than $\pm 1/2$ cycle.

The counter processor determines the Doppler difference frequency in the time domain. Timing over a selected number of cycles in the burst signal is accomplished with a crystal controlled "clock" oscillator. The frequency of the oscillator must be much higher than the Doppler difference frequency to achieve good resolution. The clock count is initiated when the high-pass filtered signal exceeds a set threshold level. A preselected number of cycles (8 or 16) are processed and used to stop the counter. Greater accuracy may be obtained by processing more cycles. Some processors, (e.g., Aerometrics) count *all* of the cycles in the burst and average the result over the number of cycles counted. This capability is especially important when the seed particles are polydisperse and produce a range of signal amplitudes. In such cases, there is the possibility of completing the preset number of cycles on the early part of the signal which has a lower signal-to-noise ratio and slew rate. There is also the possibility of reading signals from larger particles more than once.

Although the importance of attaining good quality signals cannot be overemphasized, in many practical cases the signals will be noisy. Therefore, each burst must pass certain criteria before it is accepted. The so-called periodicity check is used to reject: 1) signals with insufficient cycles, 2) signals produced by two or more particles in the measuring volume at a time, and 3) noise. Two counters are used to make period measurements over a different number of cycles, usually 5 and 8. The ratio of the two measurements is then compared to five-eighths and if they agree to a specified percentage, the signal is validated. The problem with this technique is that

the entire signal may be rejected because of a noisy cycle early in the burst. However, when the method is coupled with the three-level validation circuitry, it can be effective in rejecting spurious noise.

The three-level validation requires that a signal, Figure 2.5, exceed a positive threshold level, pass through zero, and exceed a negative threshold level before the next zero crossing is counted as a cycle. Such logic has proven to be very effective in rejecting noise. If the conditions are not met on any cycle, the counter resets and starts again almost immediately. Thus, noisy cycles on the start of a burst need not cause the loss of an otherwise good signal.

These amplified electronic signals are sent to the signal processor and ultimately to the data processor for conversion into velocities.

Ideally, an LDV needs no calibration since it provides a direct measure of the particle velocity. The fringe spacing, $\delta$, can be determined using the following formula where $\lambda$ is the laser wavelength and $\theta$ is the angle of the intersecting beams:

$$\delta = \lambda / (2 \times \sin(\theta / 2))$$

Knowing the fringe spacing and the time required for a given number of crossings, particle velocity can be determined. In practice this method can be inaccurate due to misalignment of the optics. The beam intersection angle, $\theta$, is also very difficult to compute accurately. Therefore, it is wise to test the entire system by measuring the light scattered from an object moving at a velocity that is known a priori. A rotating disk with a mark at a known radius is usually the most convenient means of doing this. However, another method (the method used in this experiment) is to measure the free stream velocity using the LDV and compare this value with that computed from the Scanivalve data.

## 3. Flow Seeding Requirements

An inconvenient characteristic of the laser Doppler velocimeter technique is the need for seed particles. The LDV actually measures the velocity of small particles that are assumed to move with the flow. If these particles do not have the appropriate size and concentration distribution, the experiment results may be adversely affected. Particle sizes on the order of 1 micron are often quoted as adequate for most gas flows and can respond to turbulence frequencies exceeding one kHz. Smaller particles may
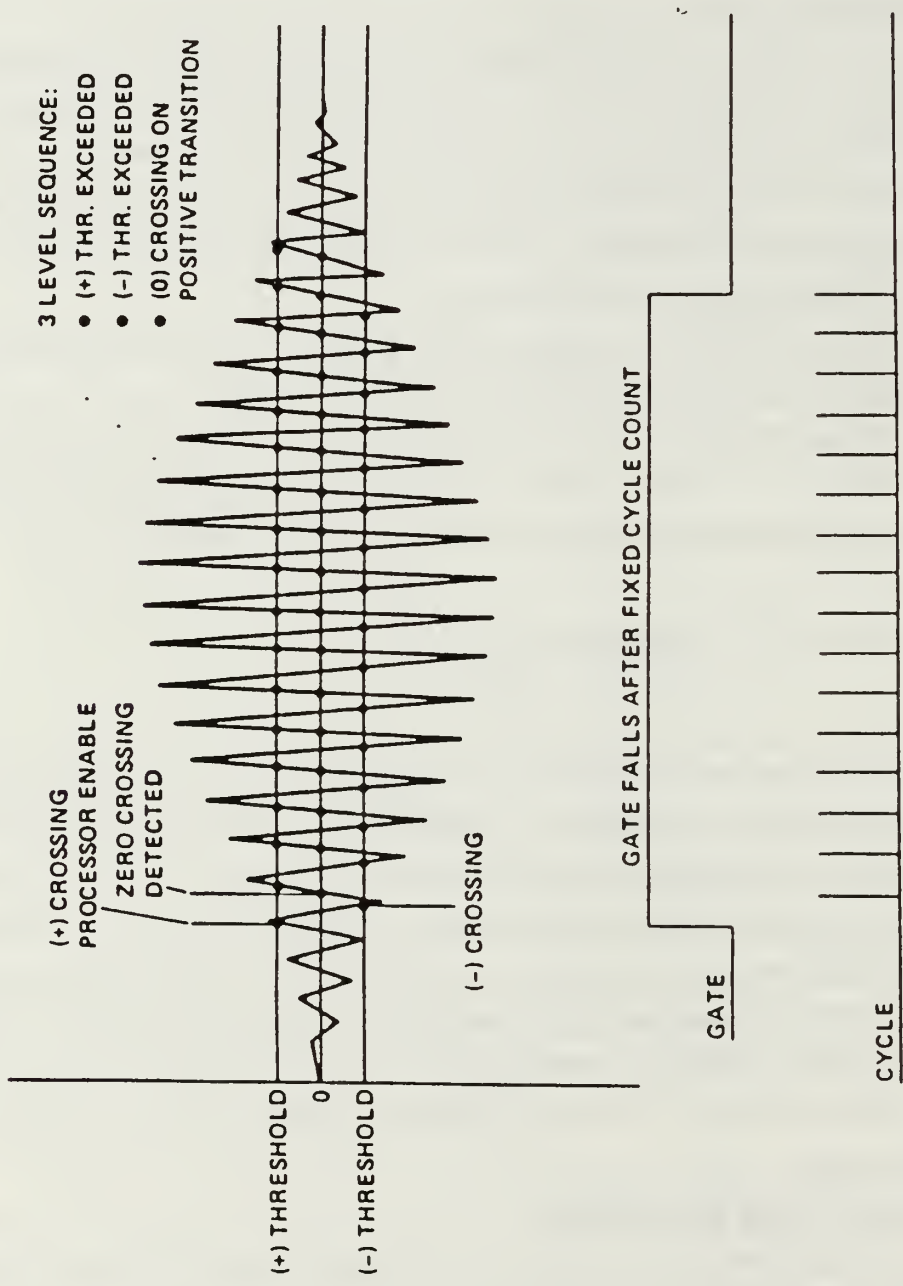
Figure 2.5   Three-level detection scheme.

be below the detectable limit of the instrument but will contribute to the background noise while larger particles that are easily detectable may not adequately track the flow.

It was determined in this experimental situation that seeding of the flow was not absolutely necessary. Several runs were made with no seeding supplied. The data obtained in these runs was accurate as dust particles acted as the flow-following agent. However, it was determined that by using a flow seeding system the data rate was increased by a factor of four to five. The system used consisted of a paint sprayer spraying latex particles (on the order of 3 microns) suspended in alcohol.

## C. COMPUTER-EXPERIMENT INTEGRATION

The experiment was fully integrated with a Data General NOVA minicomputer for on-line data acquisition and analysis, Figure 2.4. A main program ("SPOILER.FR") was written to perform all tasks and record all data required during the experiment so that individual tunnel runs proceeded virtually 'hands off'. The main program called a host of other programs during each run in order to accomplish various tasks. These other routines are listed here:

(1) "SCANI.FR" - used to obtain pressure data from the Scanivalves and compute free stream velocity and free stream Mach number. "SCANI.FR" itself calls three other routines in order to determine ambient temperature, calibration pressure and barometric pressure:

    (a) "TEMP.FR" - which yields ambient temperature from a thermocouple via an analog-to-digital converter. The thermocouple is located upstream of the test section.

    (b) "CALPRES.FR" - which calculates the output pressure from the calibration vacuum pump. The pressure value is read by this program using an analog-to-digital converter. This value is then used in the calibration of the Scanivalves.

    (c) "NPARO.FR" - which yields the value for current atmospheric pressure from a Paroscientific pressure sensor via a digital I/O.

(2) "STDTM.FR" - which gives the current time and date in order that the data files being created by the main program can be labeled.

(3) "TRELAY.FR" - to command the taskmaster to move the traverse mechanism to the next data collection location.

(4) "PLOTP.FR" - to provide on-line data analysis by allowing any of five curves to be plotted immediately after a given run.

## D. EXPERIMENTAL CONDITIONS

The free stream velocity was maintained at a nominal value of 70 m/sec, corresponding to a Reynolds number of $7.4 \times 10^5$ based on the airfoil chord. Experiments were carried out with the spoiler deflected 30 degrees and the angle of attack at 0 and 5 degrees. Locations where data was obtained are shown in Figure 2.6.

23
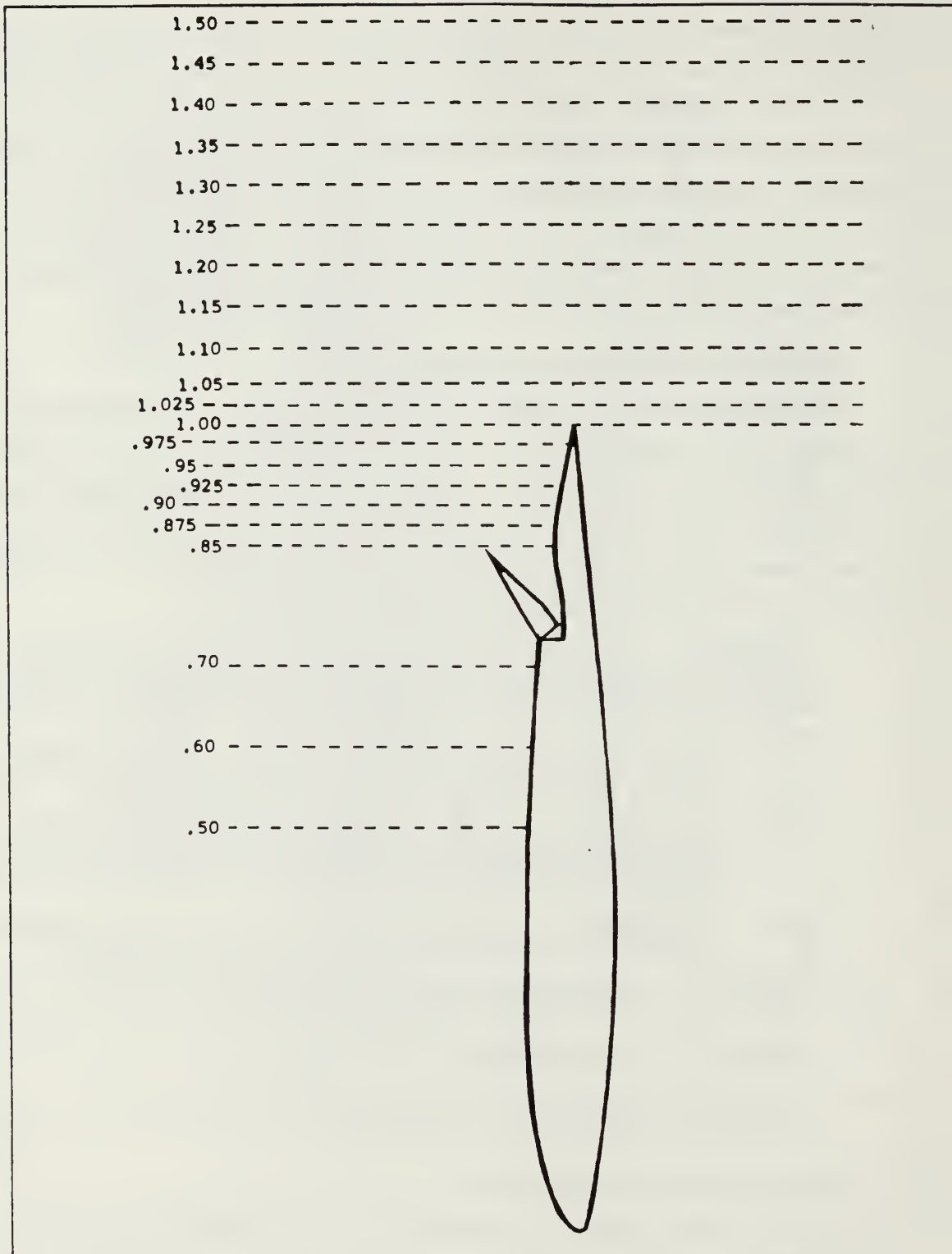
Figure 2.6   Data collection locations.

In order to determine the velocity profiles, data was acquired at varying steps based on the velocity gradient. Fine step sizes were taken near the airfoil for boundary layer profiles and near free shear layers in the wake measurements. Typically, 15 data points were taken in the boundary layer and 20 points in the wake. The 4-beam LDV arrangement precluded obtaining data closer than 0.1 inch from the airfoil surface, however.

The boundary layer traverse was along the vertical axis of the test section, so the traverse direction is not normal to the airfoil surface as are usual boundary layer profiles. Angle of attack and model surface curvature make the measurement axis incline to the model.

# III. DATA ACQUISITION

## A.    FREE STREAM VELOCITY

At the beginning of every run, the main experiment-driving program ("SPOILER.FR") calls for the Scanivalve pressures, ambient temperature, calibration pressure and atmospheric pressure to be read. Assuming isentropic flow in the test section upstream of the airfoil and away from any shock waves, the free stream Mach number, M, can be calculated from the stagnation pressure, $P_o$, and the static pressure, P, along the wall:

$$M = \{((P_o/P)^{(\gamma-1)/\gamma} - 1)(2/(\gamma-1))\}^{1/2}$$

For $\gamma = 1.4$:

$$M = \{((P_o/P)^{(2/7)} - 1) \times 5\}^{1/2}$$

Then, velocity is given by:

$$V = Ma$$

where

$$a = \sqrt{\gamma RT}$$

T is obtained from the total temperature, $T_o$, using the following formula:

$$T = T_o/\{1 + ((\gamma-1)/2) \times M^2\}$$

$T_O$ is measured by a thermocouple at the wind tunnel inlet.

The above method is used to obtain free stream Mach number and free stream velocity for every run. The value for free stream velocity is used in the data reduction process to normalize the airfoil velocities obtained from the LDV.

## B.  AIRFOIL VELOCITIES

Processing of the Laser Doppler Velocimeter data obtained during this experiment was carried out using the same Data General Nova digital computer and driving program used for all other experiment functions. "SPOILER.FR", the main program for this experiment, calls a digital I/O driver program ("DIO24") to read words as fast as possible from two cards (these cards receive the digital output from the two Macrodyne channels, one for each LDV component). As soon as 1000 samples (per component) have been taken by the Macrodyne processor and read by DIO24, the binary output from each sample is converted to decimal using a decoding subroutine ("DECODE1.FR").

As mentioned earlier, the Macrodyne signal processor used in this experiment utilizes a 1 GHz counter. The number of "counts" required for the passage of 8 cycles is sent to the digital I/O in the form of a 10-bit mantissa and 4-bit exponent, namely

$$D_9, D_8,...D_0 \times 2^{exp}$$

For example, if 400 "counts" were required for a particular Doppler burst, the output would be

$$\begin{array}{cc} 0000110010 & 0011 \\ \text{Mantissa} & \text{EXP} \end{array}$$

which, upon decoding, reduces to

$$50 \times 2^3 = 400$$

Since the clock counts are produced at 4 GHz (the 1 GHz clock is divided into 4 phases), each clock count is 0.25 nanoseconds. Thus,

$$t_s = D_9, D_8, ... D_0 \times 2^{exp} \times \frac{(0.25)}{(8.0)} \text{ ns}$$

is the period of the signal when 8 cycles are measured.

Converting this to signal *frequency*, $f_s$, yields

$$f_s = \frac{1}{t_s} = \frac{2^{5-exp} \times 1000}{\text{Mantissa}} \text{ MHz}$$

Since the *signal* frequency, $f_s$, is composed of the Doppler frequency, the shift frequency and the mixing frequency, the Doppler frequency can be obtained from

$$f_D = f_s - f_{shift} + f_{mix}$$

Once the Doppler frequency of a particle is known, its velocity can be determined from

$$\text{velocity} = \text{const} \times f_D$$

where "const" is determined based on the fringe spacing or direct calibration.

With the 1000 samples from each component converted to decimal, the data can be reduced to average and rms velocities using the formulas found in Table II. This data (both raw and reduced) is then stored for future analysis.

While most data analysis is performed after completion of the experiment, several on-line analysis routines are available for use as real time performance checks. For example, "HISTOGRAM.FR" is a program available to first read a given number of samples from one of the Macrodyne channels and plot frequency versus the number of

samples at each frequency in histogram fashion. With this program it is easy to determine whether or not the data is conforming to the Normal Distribution (to which ideal data should conform). Another on-line analysis tool which is built into the main program "SPOILER.FR" is the subprogram "PLOTP.FR". This routine gives the experimenter the option to have any of five velocity profiles (i.e., $U_{ave}/U_\infty$, $V_{ave}/V_\infty$, etc.) plotted on the screen immediately after completing an experimental run. This subprogram was used extensively to immediately inspect the quality of each run.

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TABLE II

VELOCITY PROFILE AND TURBULENT STRESS EQUATIONS

$$\overline{U} = \frac{1}{N} \sum_{i=1}^{N} U_i;$$

$$\overline{V} = \frac{1}{N} \sum_{i=1}^{N} V_i;$$

$$\overline{u^2} = \frac{1}{N} \sum_{i=1}^{N} U_i^2 - \overline{U}^2;$$

$$\overline{v^2} = \frac{1}{N} \sum_{i=1}^{N} V_i^2 - \overline{V}^2;$$

$$\overline{uv} = \frac{1}{N} \sum_{i=1}^{N} U_i V_i - \overline{U}\overline{V}.$$

---

## C. REYNOLDS SHEAR STRESSES AND TURBULENT STRESSES

Table II shows the equations used to determine mean velocities, turbulent stresses and Reynolds shear stress throughout this experiment. The value for N was generally 1000 since this was the number of velocity samples taken at each measurement location (for each component).

# IV. RESULTS AND DISCUSSION

## A. INTRODUCTION

One of the purposes of this experiment was to demonstrate the benefits of the two-component Laser Doppler Velocimeter by employing this type of system to measure the flow field of an airfoil with a deflected spoiler. In order to present the results of these measurements effectively, a graphics program called "PLOT-3D" was used to plot the data obtained. "PLOT-3D" is available on the VAX system at the NASA Ames Research Center.

A data interpolation routine written by Chyang Sheng Lee of Stanford University was also used to interpolate the measured data into a grid system so that it could be plotted. All of the contour plots presented use the interpolation routine to interpolate in both the x and y directions. However, some of the velocity vector plots use interpolation in the y direction only. This was done because, in some cases, linear interpolation of the data gives a false impression of what the flow field is actually doing.

In all cases, the data presented in this section is for $\alpha = 0°$ and $\delta = 30°$.

## B. FLOW FIELD ANALYSIS

Velocity measurements were taken at a variety of points along the upper surface ahead of and behind the spoiler. Figure 4.1 shows a plot of the data obtained over the rear portion of the airfoil. Note the low-velocity, recirculating flow region directly behind the spoiler.

While the data for Figure 4.1 was interpolated in the y direction only, the data for Figure 4.2 was interpolated in both the x and y directions. It can be seen in Figure 4.2 that interpolation in the x direction yields some fairly unrealistic velocity vectors due to the relatively low number of measurement locations as compared to the number of grid points. For example, those directly ahead of the spoiler. On the other hand, complete interpolation (in both the x and y directions) does serve to paint a good overall picture of what the flow field is doing based on a finite number of velocity measurements.
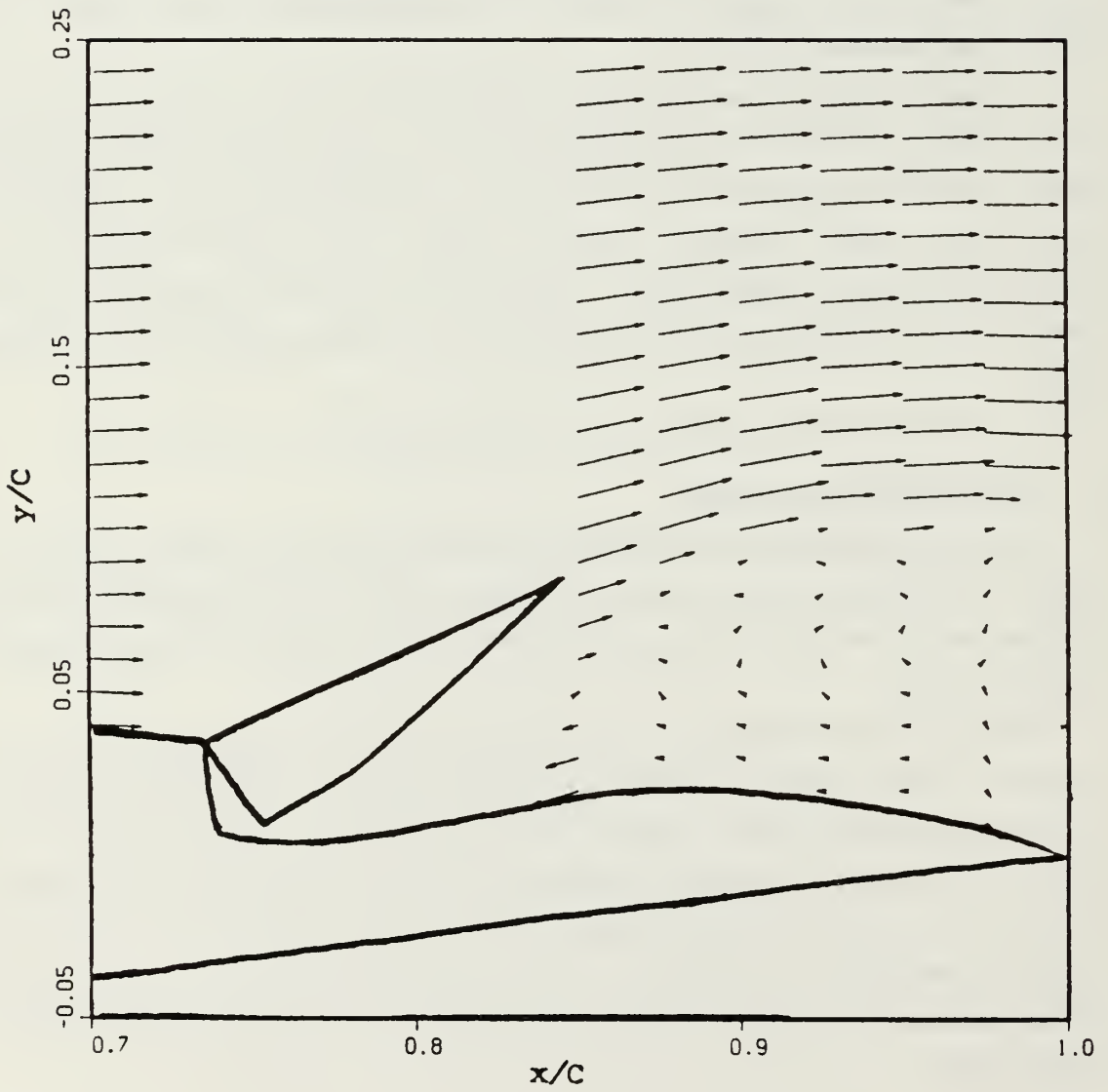
Figure 4.1    Flow field measured over rear portion of airfoil
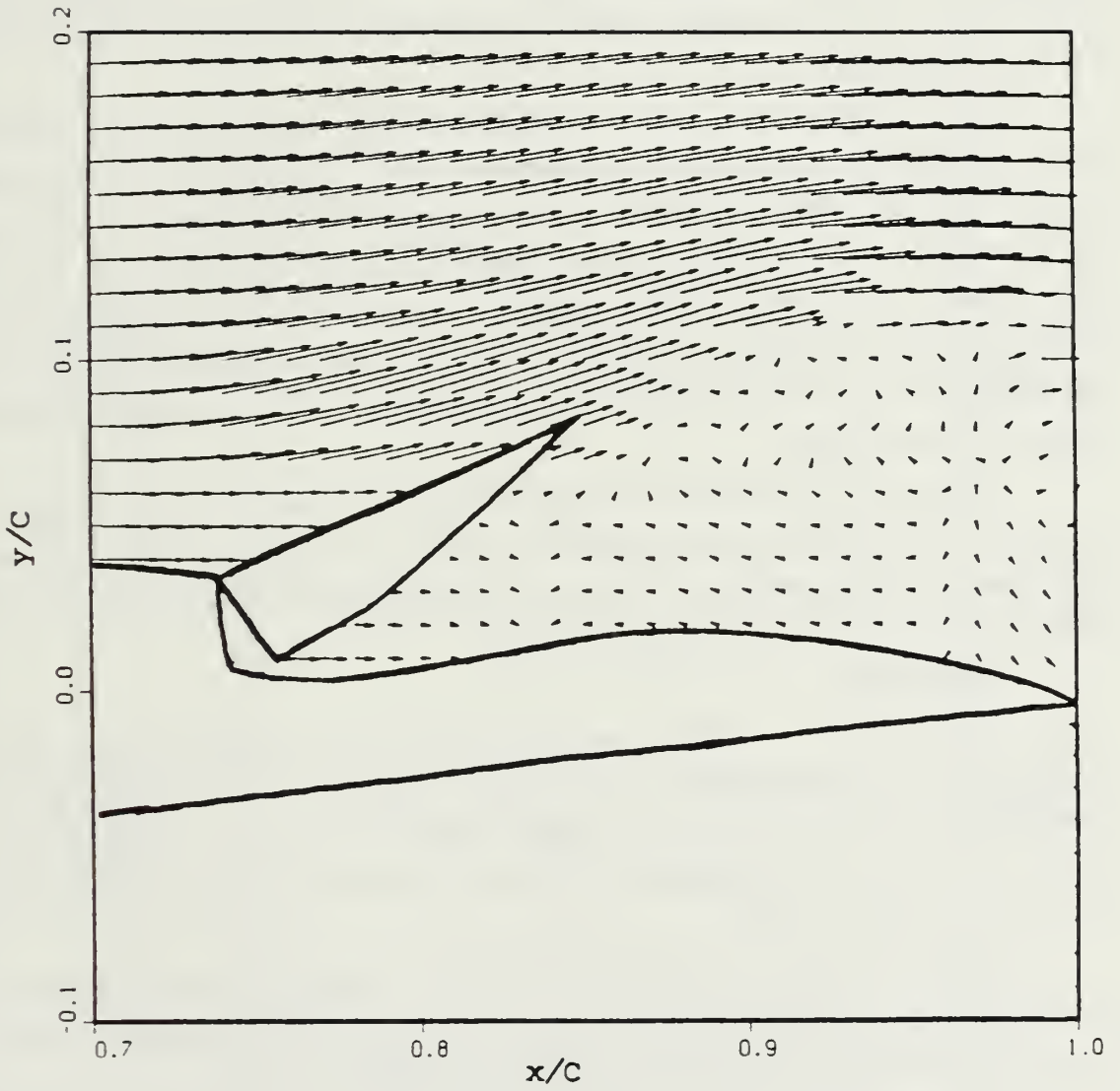(interpolation in y direction only).

Figure 4.2    Flow field measured over rear portion of airfoil
(interpolation in both directions).

## C. WAKE

The wake behind the spoiler was measured with the two-component LDV system at numerous locations to determine the mean and rms profiles. The results from the wake are presented in this section.

### 1. Wake Profiles

The mean longitudinal and transverse wake profiles measured by the LDV for $\alpha = 0°$ and $\delta = 30°$ are presented in Figures 4.3 and 4.4. The symbols are the measured data and the lines represent the best fit curves of the data. As expected, the width of the wake, the velocity defect and transverse velocity all decrease in the downstream direction.

The Reynolds shear stress, longitudinal and transverse turbulent stresses measured by the LDV are presented in Figures 4.5 to 4.7. Obvious in all three of these figures is the fact that the fluctuating region appears to grow from the $x/C = 1.0$ (trailing edge) location to $x/C = 1.25$ then decrease as it approaches $x/C = 1.5$. The "S" shape profile in the Reynolds shear stress is typical for a two-dimensional wake [Ref. 1:p. 29]. The longitudinal and transverse turbulent stresses show two peaks at the locations where the two free shear layers (corresponding to the airfoil and the spoiler) oscillate in the near wake.

Figures 4.8 and 4.9 show the velocity vectors in the wake. A scaled profile of the airfoil is superimposed in each figure for reference. The data in Figure 4.8 was interpolated in the y direction only. Figure 4.9 was interpolated in both directions and depicts the mean wake velocity profile quite well.

### 2. Contour Plots

Figures 4.10 to 4.16 depict "contour" plots of various quantities in the airfoil wake. Figure 4.10 shows regions of equivalent U-magnitude (U is referenced to free stream velocity). Note that there are regions where the ratio $U/U_\infty$ is greater than unity. This is due to tunnel blockage effects which cause the flow to accelerate more than normal around the airfoil.

Figure 4.11 depicts the regions of equivalent V-magnitude (also referenced to free stream velocity). A minus sign on a contour line in Figure 4.11 implies that the V component of velocity is negative (downward) in that region.

In Figure 4.12, the *total* velocity magnitudes in the wake are contoured. Again, contour lines with values greater than one arise due to blockage effects.

34
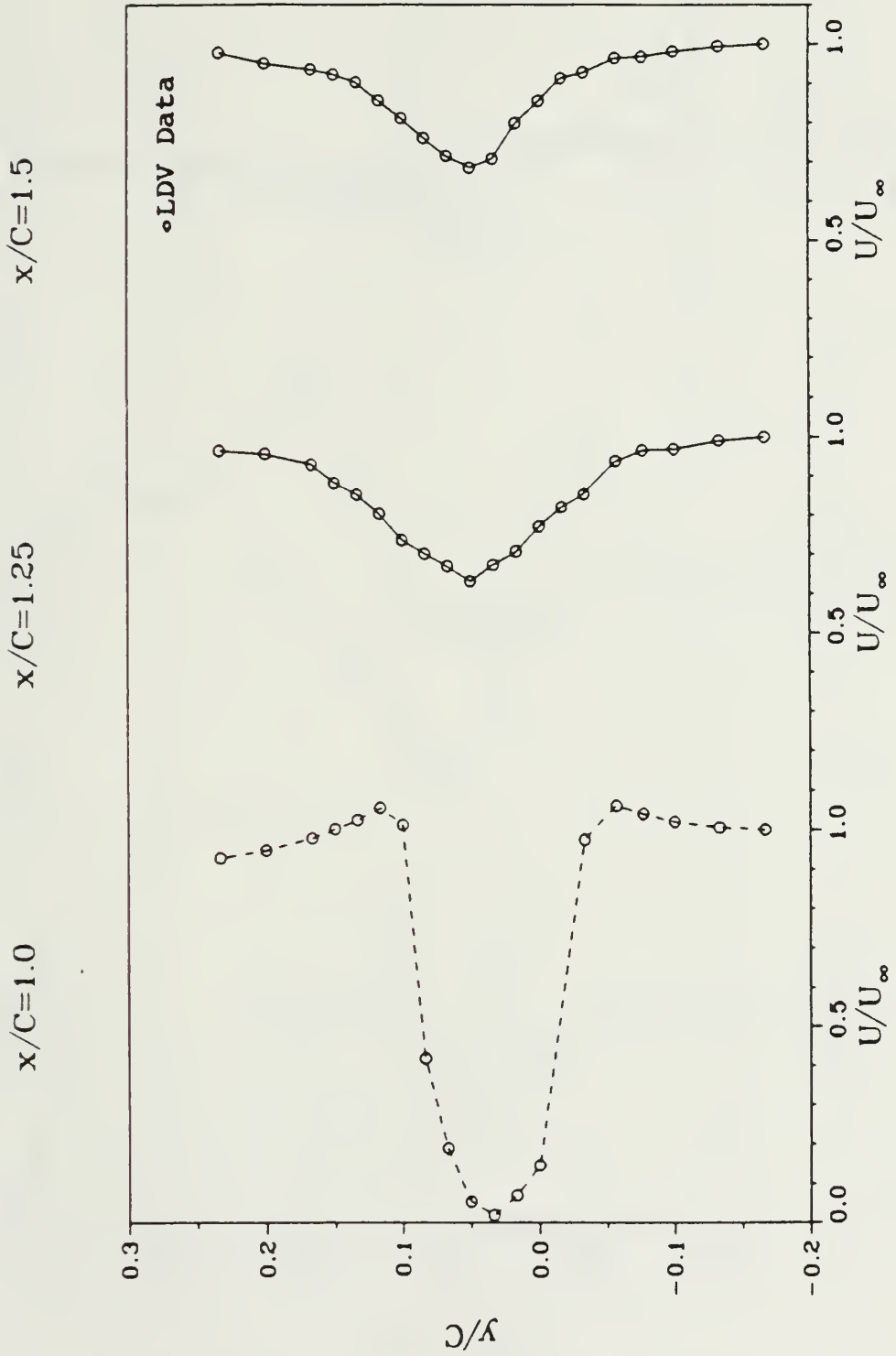
Figure 4.3  Longitudinal velocity profiles in the wake.

35
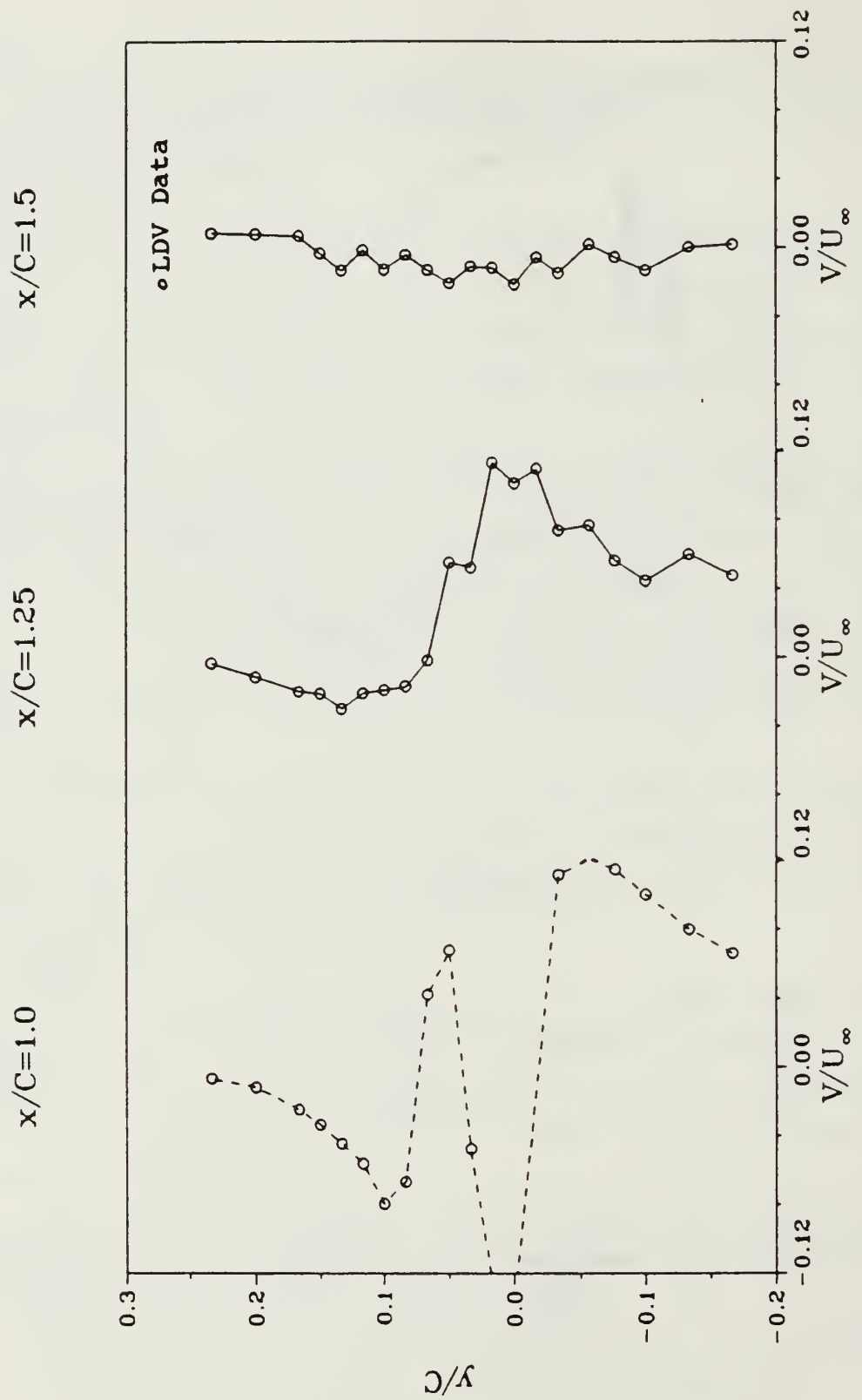
Figure 4.4    Transverse velocity profiles in the wake.

36
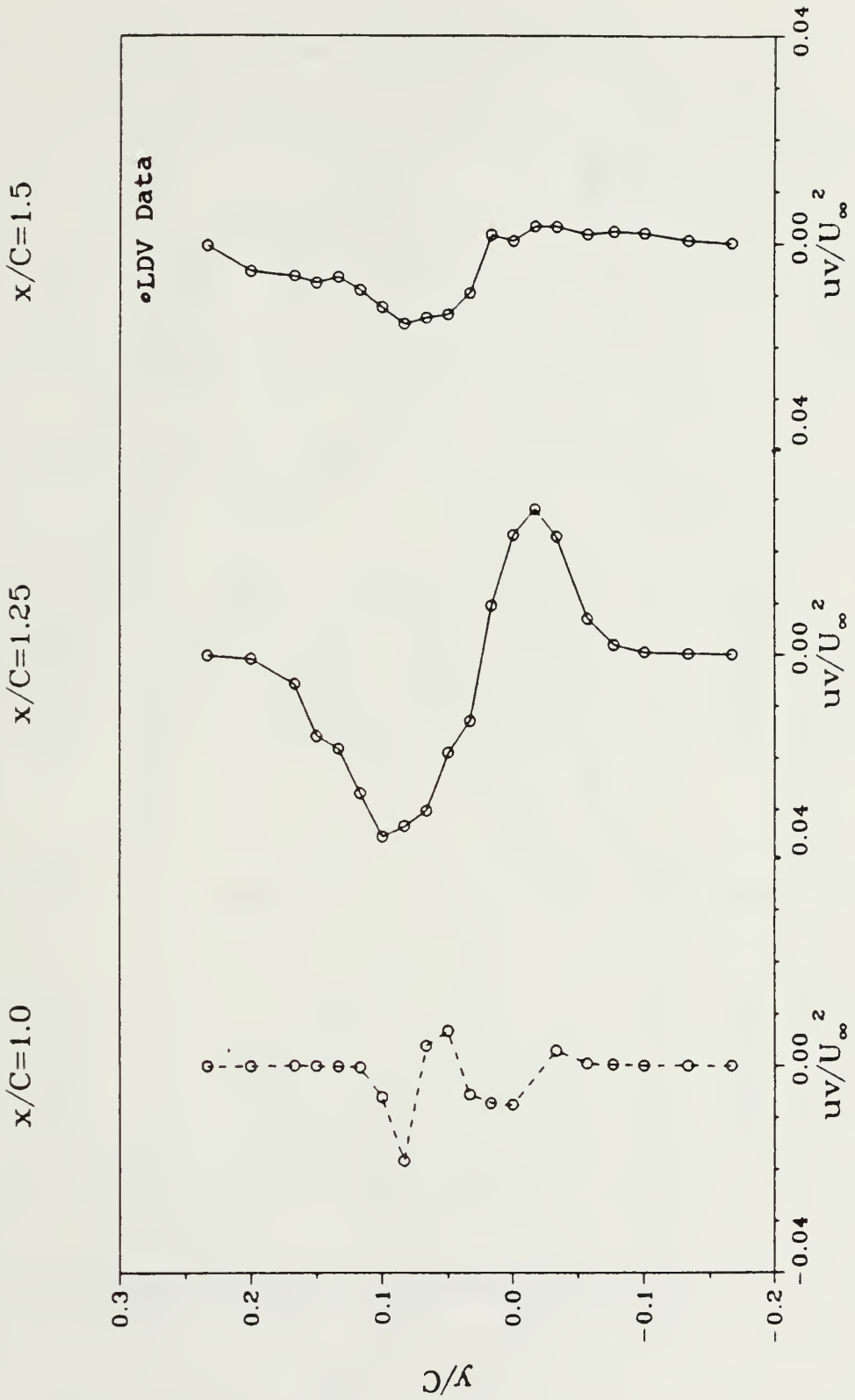
Figure 4.5    Reynolds shear stress in the wake.
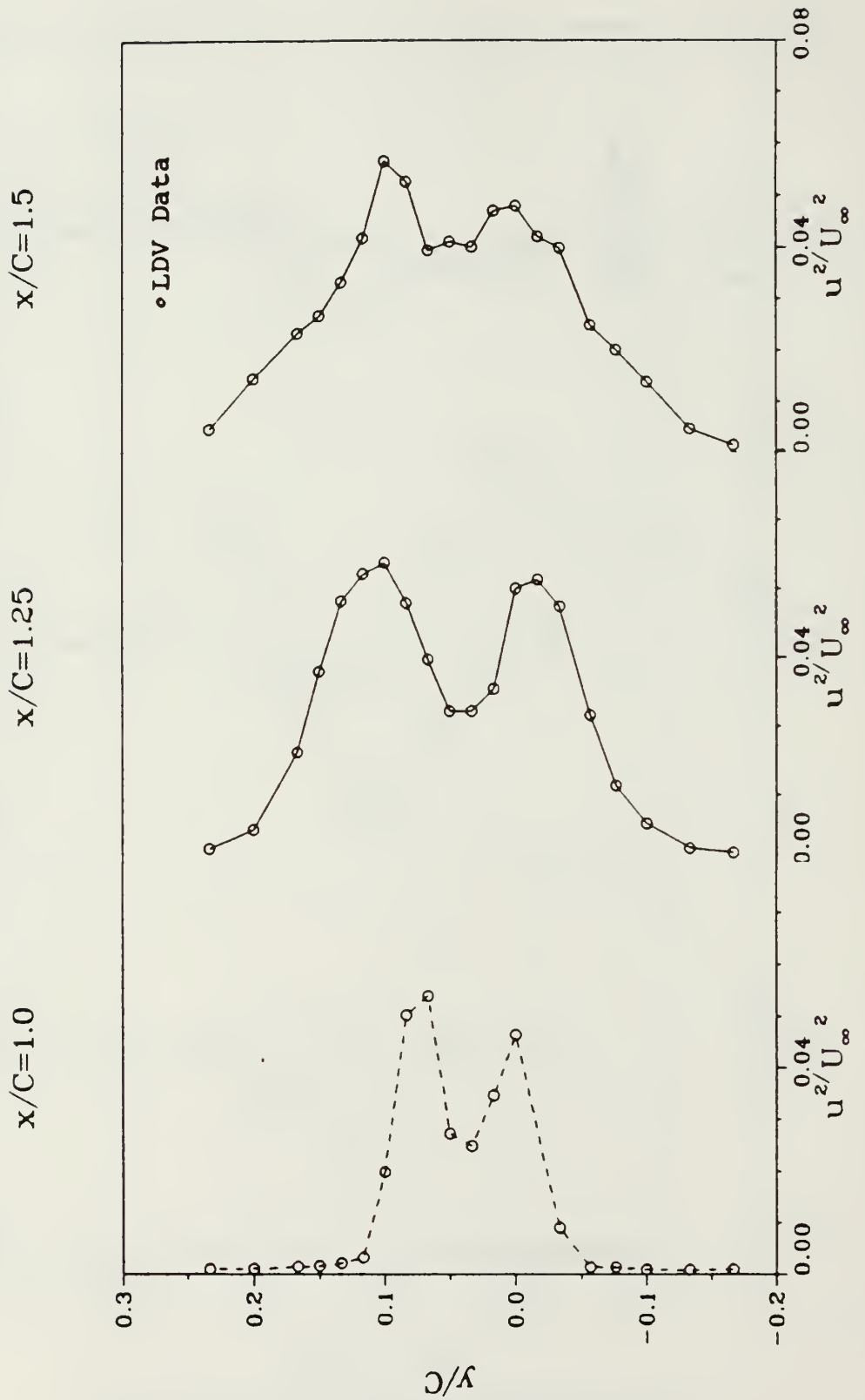
Figure 4.6   Longitudinal turbulent stress in the wake.

38
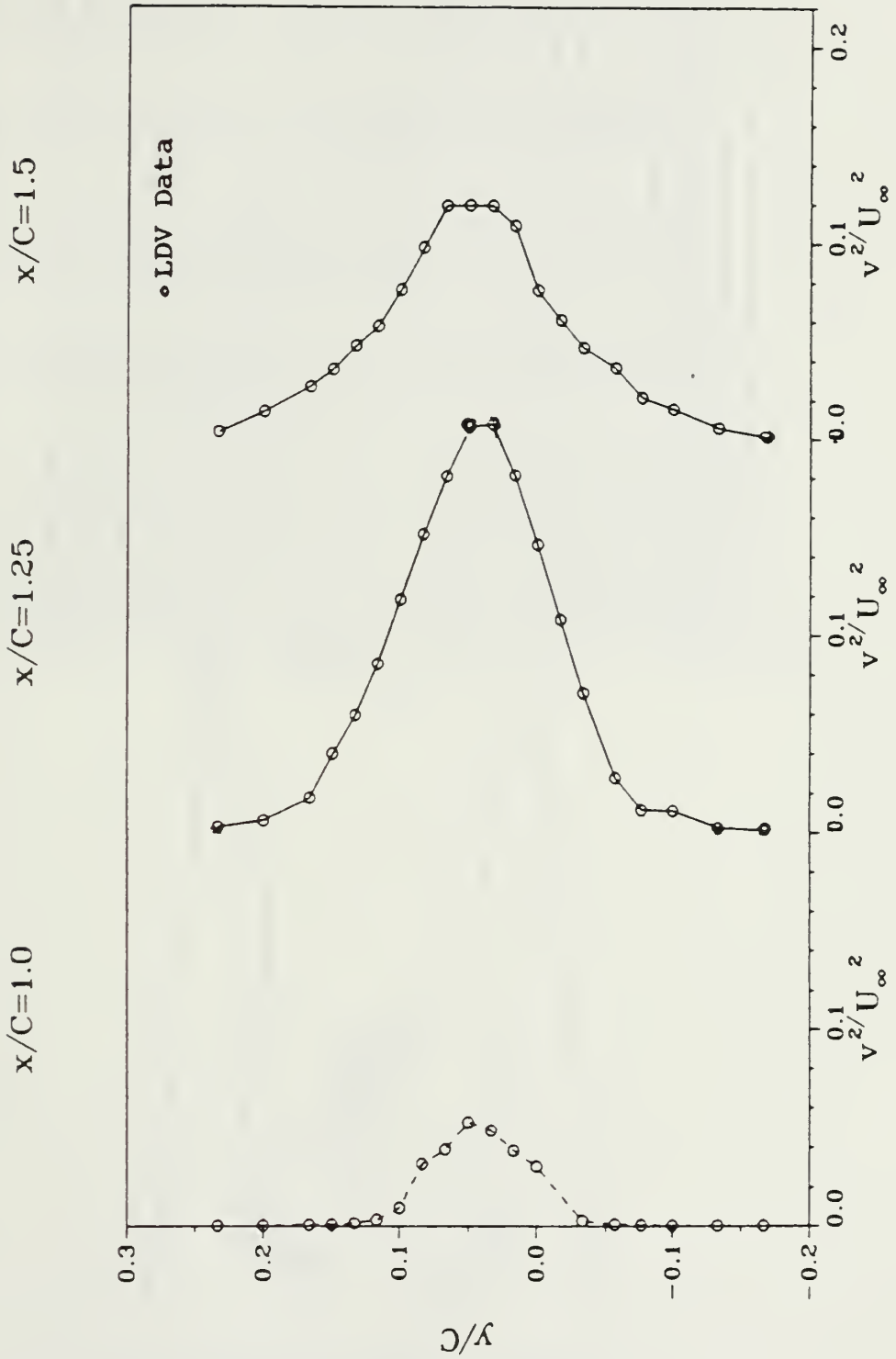
Figure 4.7   Transverse turbulent stress in the wake.
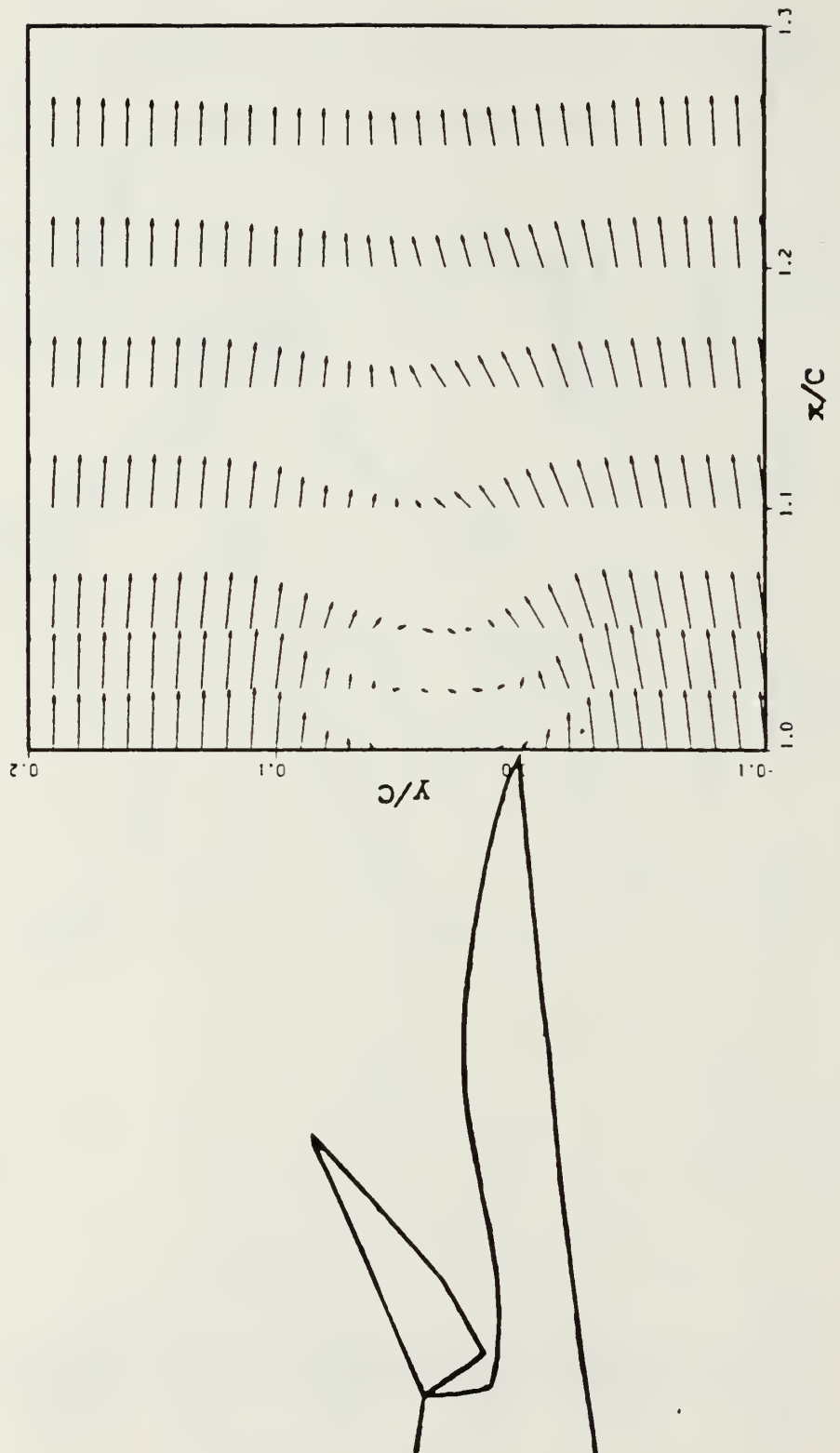
Figure 4.8 Velocity vectors in the wake
(interpolation in y direction only).

40
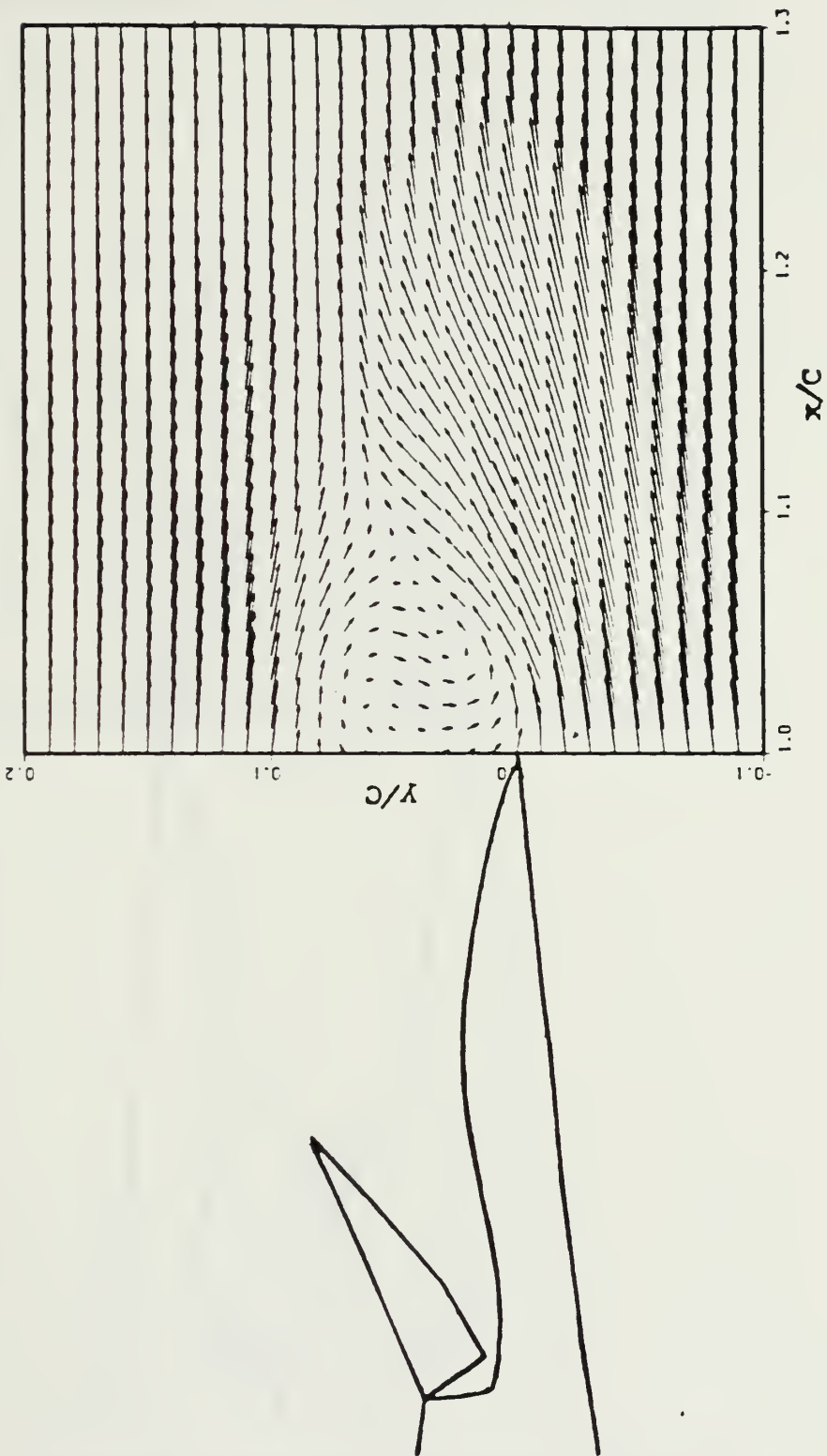
Figure 4.9   Velocity vectors in the wake
(interpolation in both directions).

41
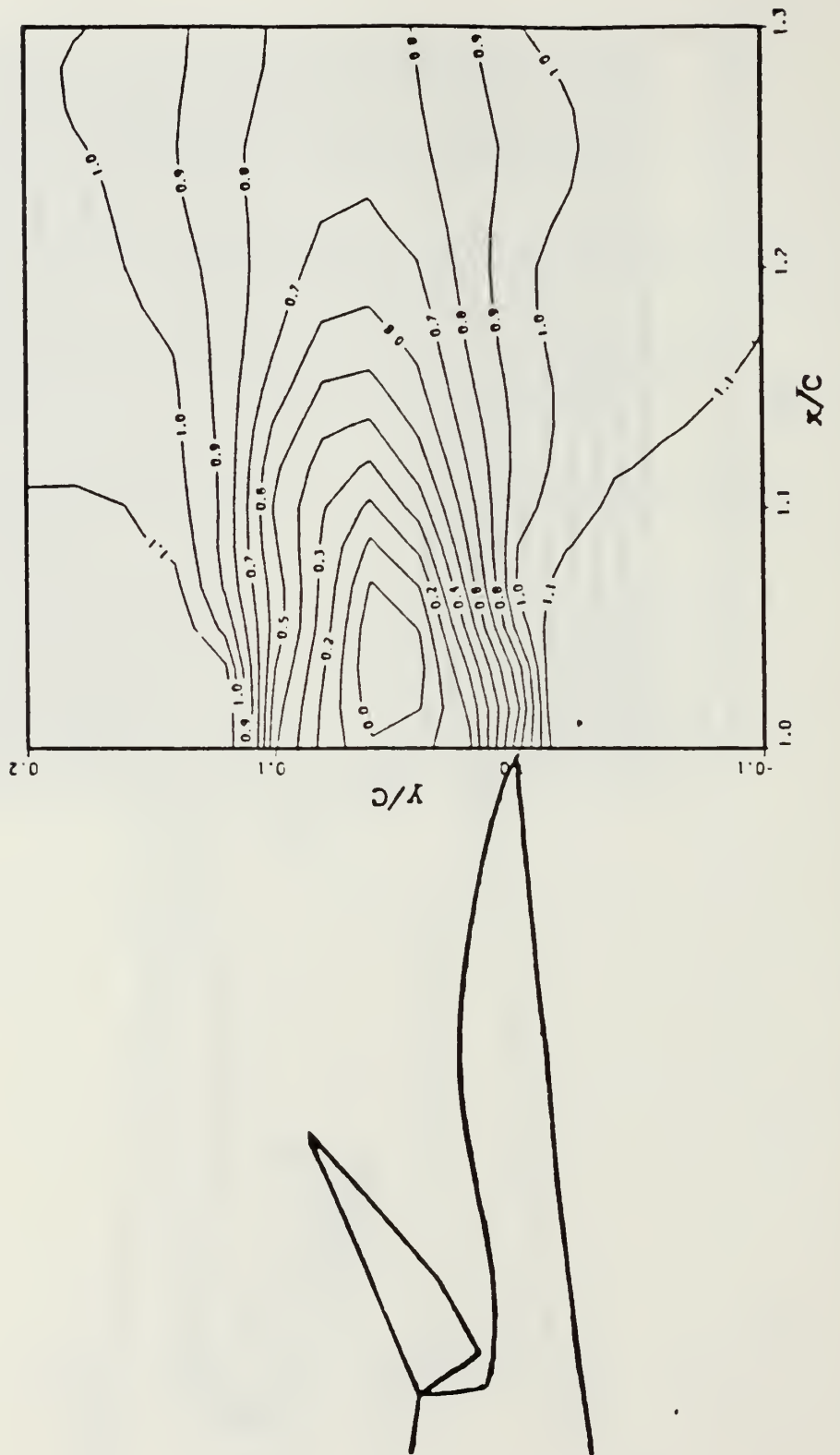
Figure 4.10   Contour plot of U-magnitude in the wake.

42
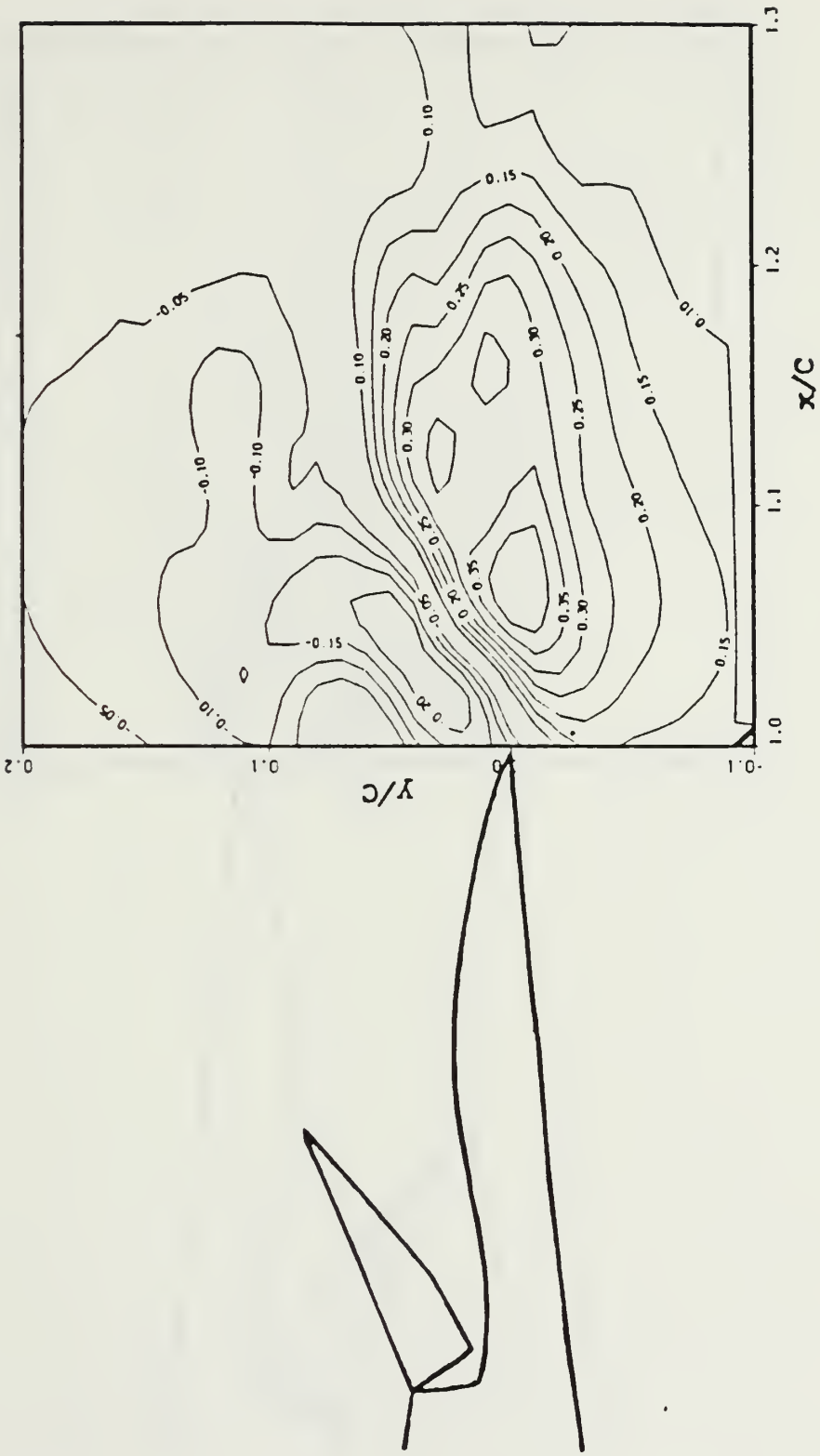
Figure 4.11   Contour plot of V-magnitude in the wake.

43
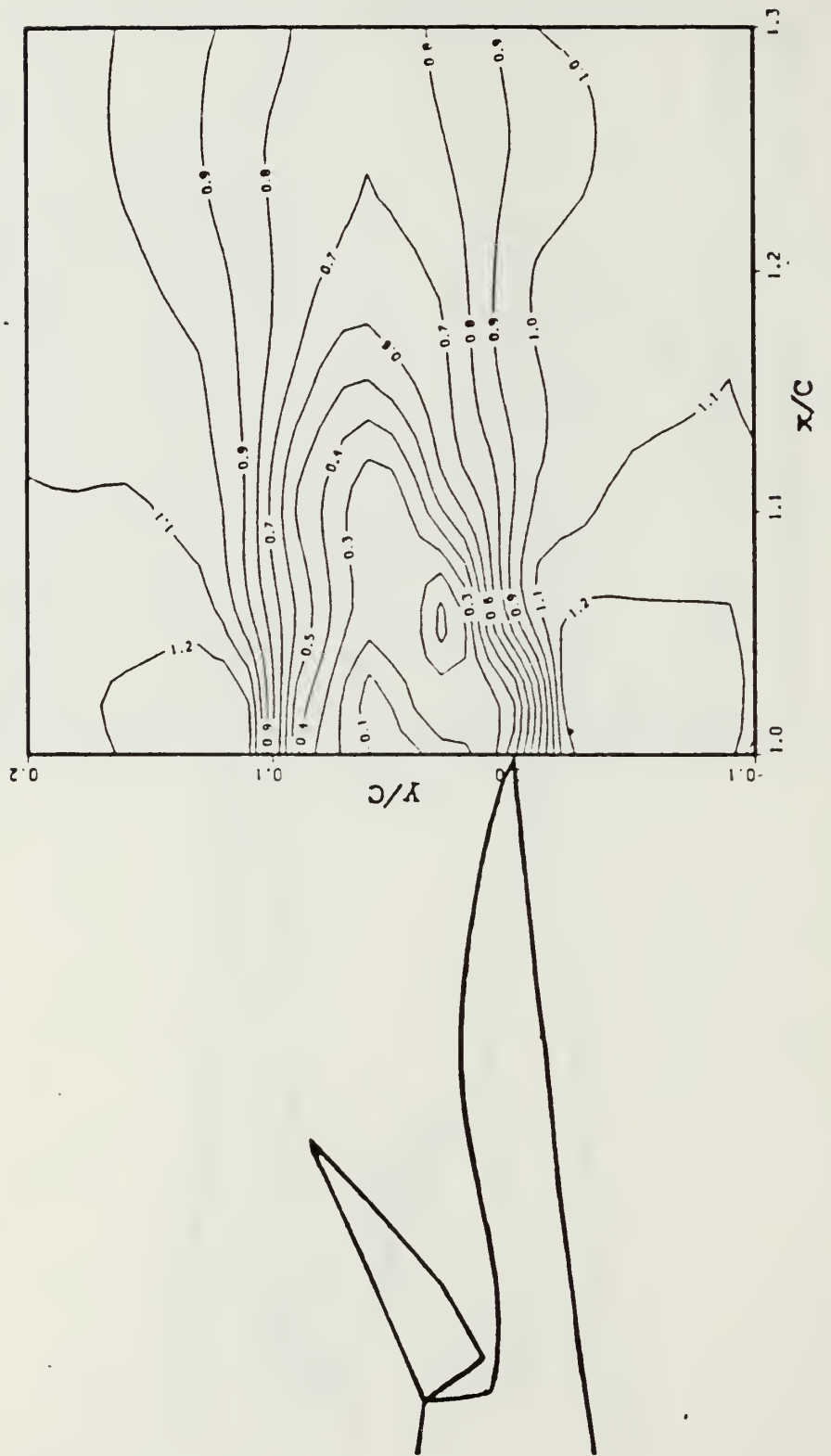
Figure 4.12    Contour plot of total velocity magnitudes in the wake.
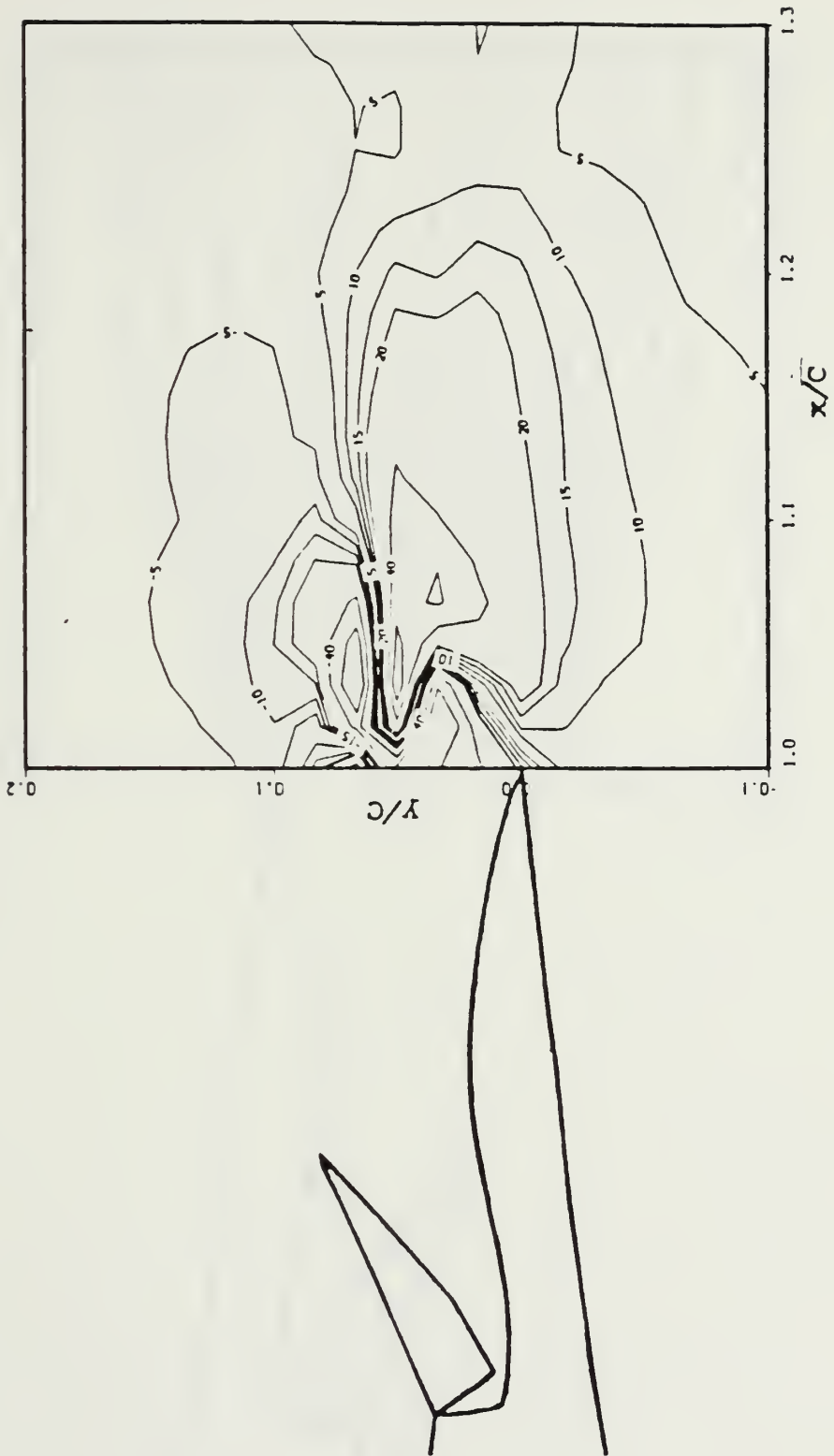
Figure 4.13    Contour plot of flow angles in the wake.
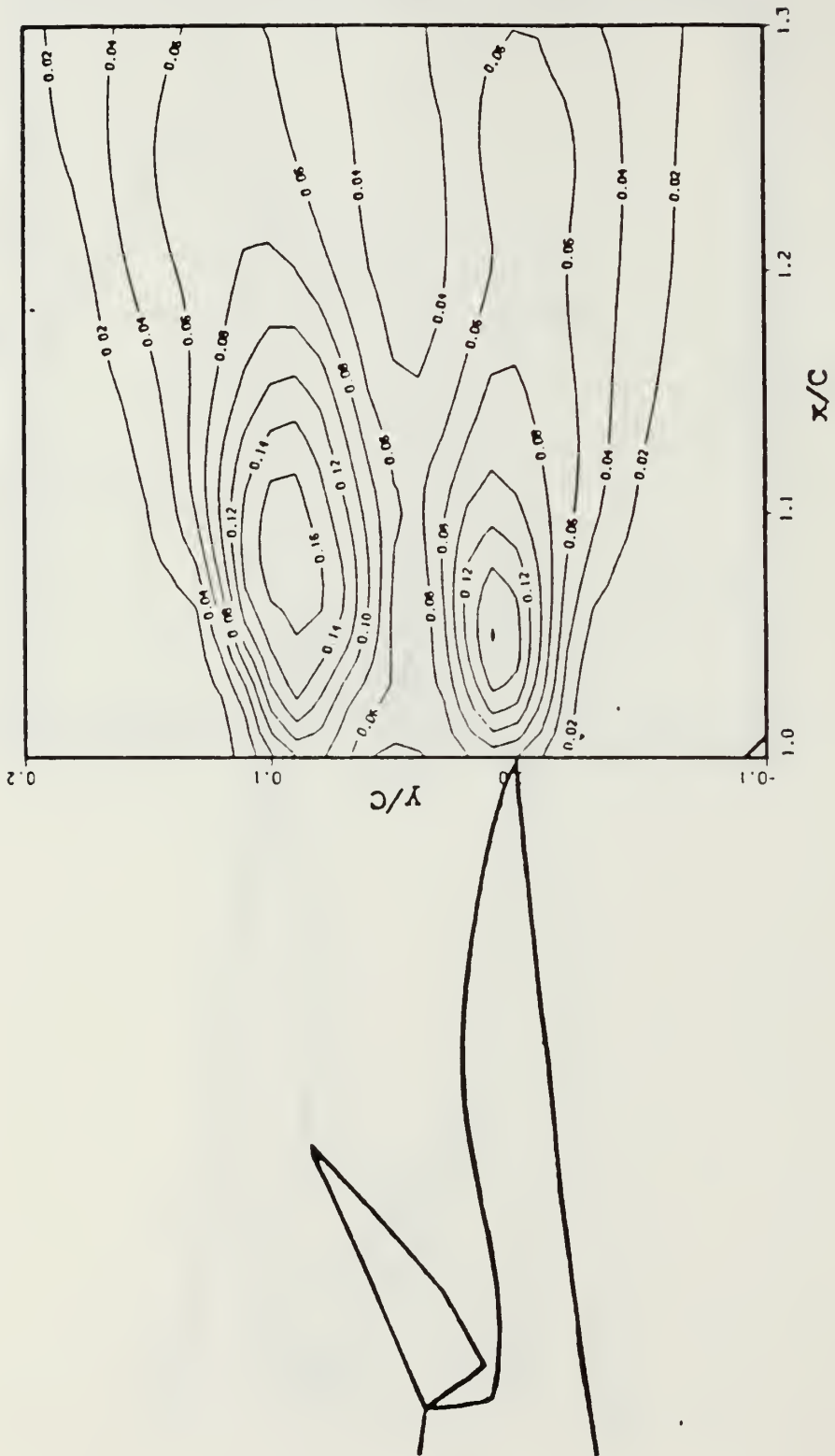
Figure 4.14   Contour plot of longitudinal turbulent stresses in the wake.

46
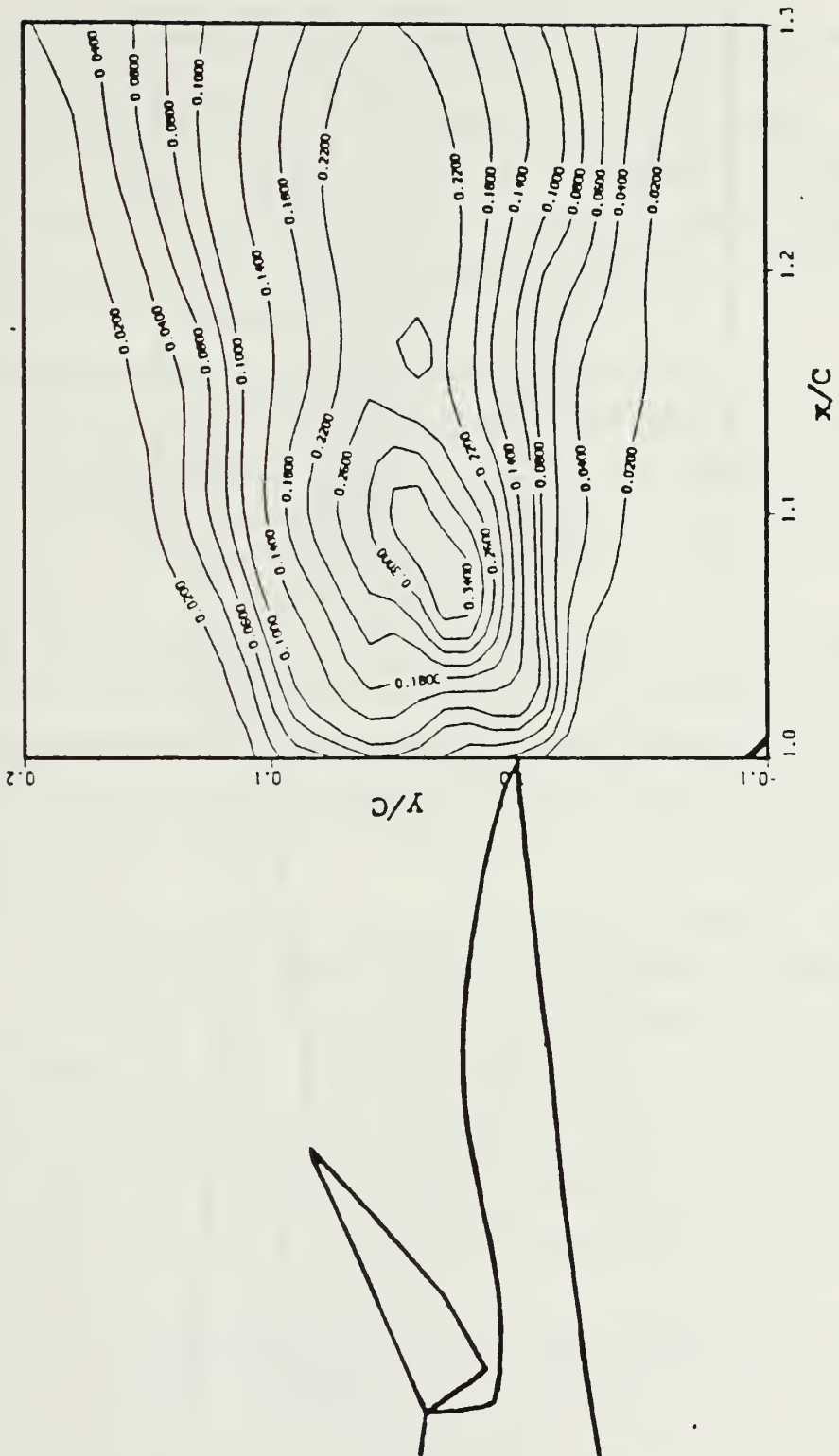
Figure 4.15    Contour plot of transverse turbulent stresses in the wake.

47
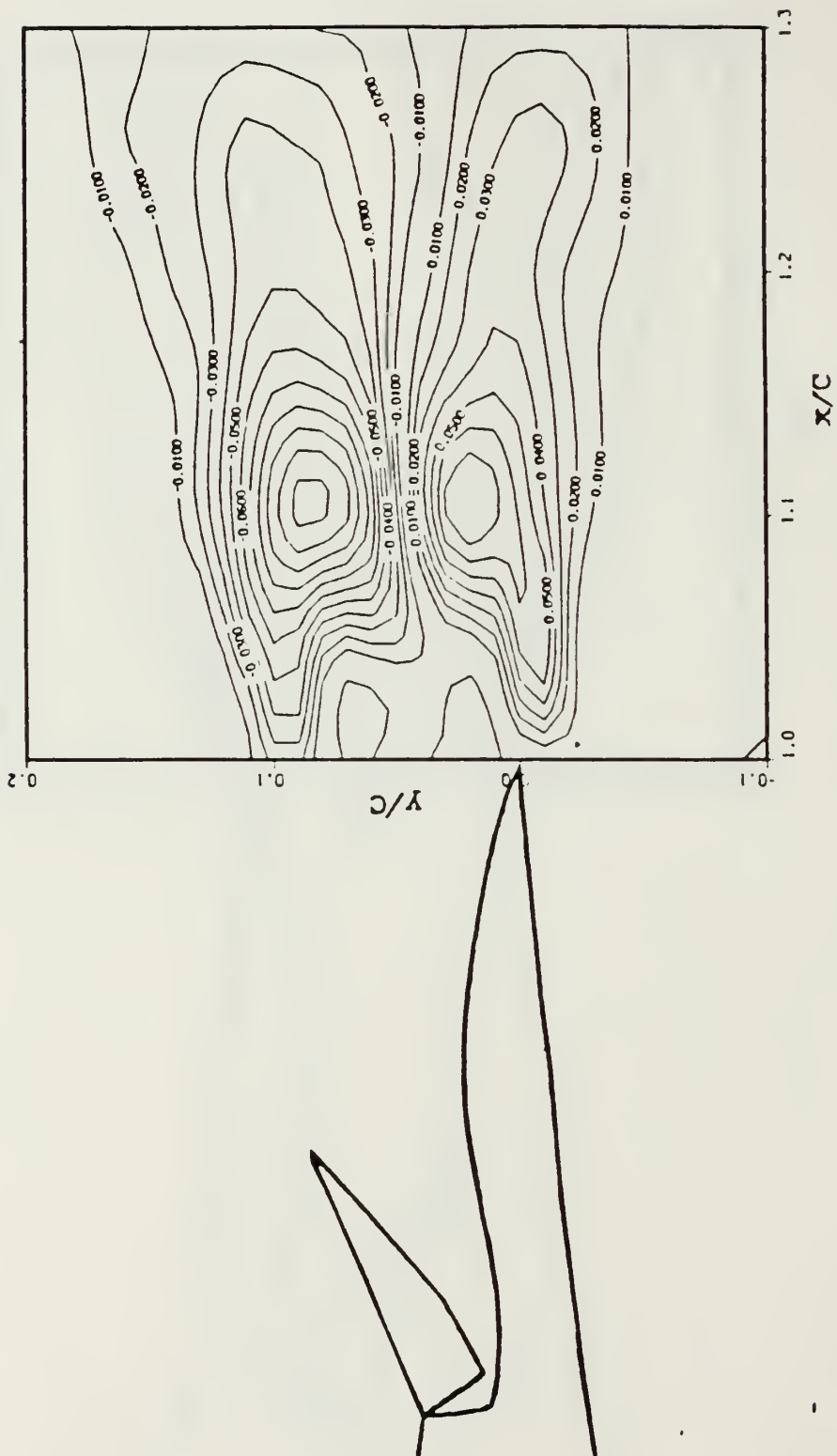
Figure 4.16   Contour plot of Reynolds shear stresses
in the wake.

48

Figure 4.13 shows how rapidly the flow angles change in the near wake (the closer the contour lines, the steeper the gradient).

Longitudinal and transverse turbulence and Reynolds shear stress are contoured in Figures 4.14 to 4.16. Figure 4.14 clearly shows the two regions where the turbulence intensity is the highest. These two regions are probably caused by counter-rotating vortices originating at the spoiler trailing edge (clockwise vortex) and the airfoil trailing edge (counterclockwise vortex).

## D.    COMPARISON WITH HOT-WIRE ANEMOMETER DATA

One purpose of this thesis was to compare the data obtained in this experiment with the hot-wire data obtained under similar conditions by Lee [Ref. 5]. Figures 4.17 to 4.21 are LDV/hot-wire comparisons of longitudinal and transverse velocity, longitudinal and transverse turbulent stress, and Reynolds shear stress at three locations in the wake.

It is important to mention that, in the previous experiment, no hot-wire data was obtained in the region of reverse flow between $x/C = 1.0$ and $x/C = 1.25$. Hot-wire anemometry is virtually unusable in this region due to the fact that hot-wires *rectify* the signals, which include the instantaneous forward velocity as well as the reverse velocity. Consequently, velocities measured by hot-wires in reverse flow regions appear higher than they actually are.

Except for minor grid alignment errors in the y direction, most of the curves are in very good agreement. As expected however, the longitudinal turbulence stress curves at $x/C = 1.25$ (Figure 4.19) and the transverse turbulence stress curves at $x/C = 1.25$ (Figure 4.20) show considerable disagreement. In the longitudinal turbulence case, the hot-wire data shows *more* turbulence in the middle of the wake while in the transverse turbulence case, the hot-wire data shows *less* turbulence in the middle of the wake. This is again due to the fact that hot-wire measurements give a misleading velocity profile close to the trailing edge because of the reverse flow in that region [Ref. 1:p. 70].

The hot-wire anemometer is quite accurate in regions where there is no reverse flow. However, in order to obtain reliable data on the mean velocities and turbulent stresses in the reverse flow regions and the near wake of this airfoil-spoiler system, Laser Doppler Velocimetry yields better results.
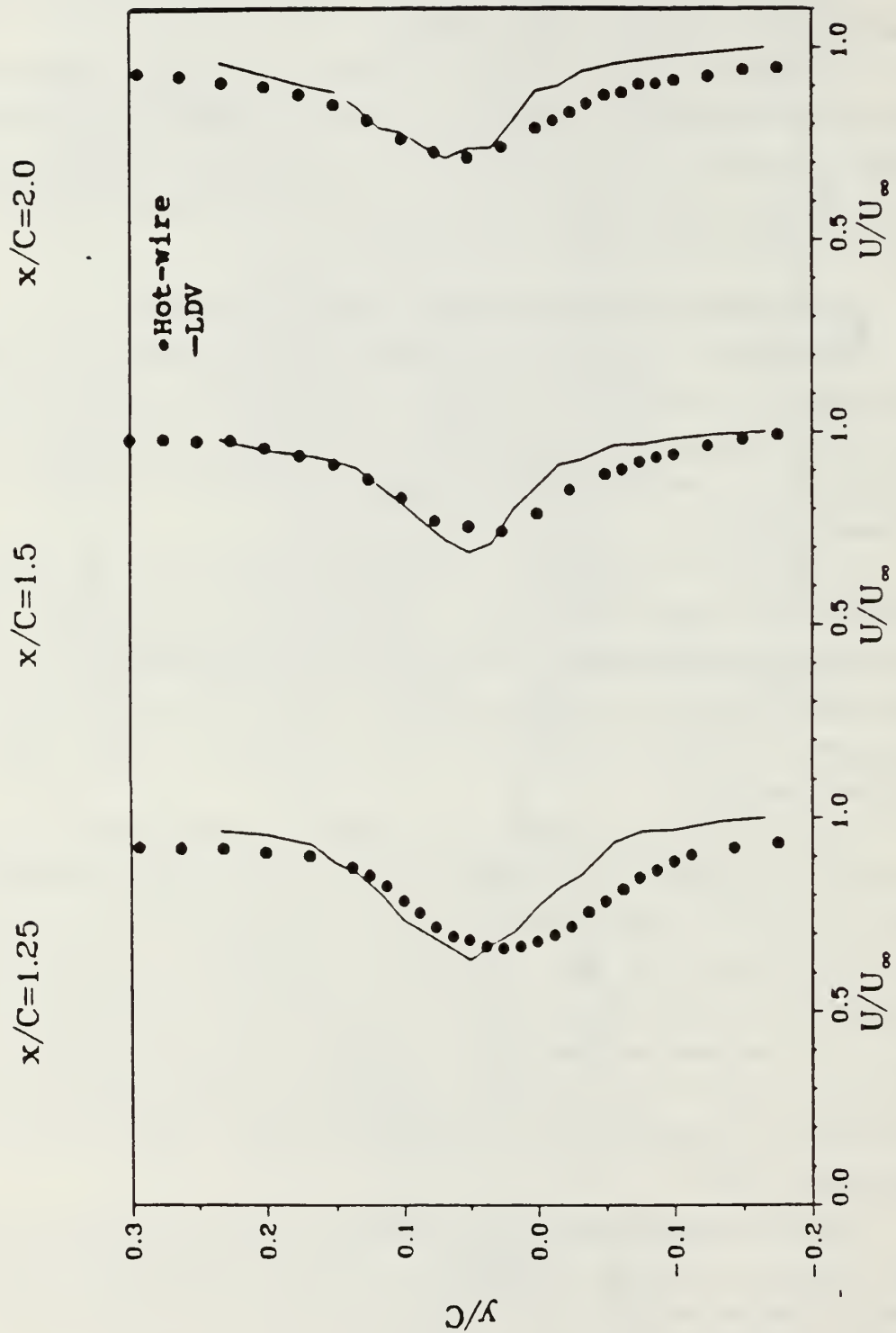
Figure 4.17    Comparison of LDV and hot-wire data for
longitudinal velocity.
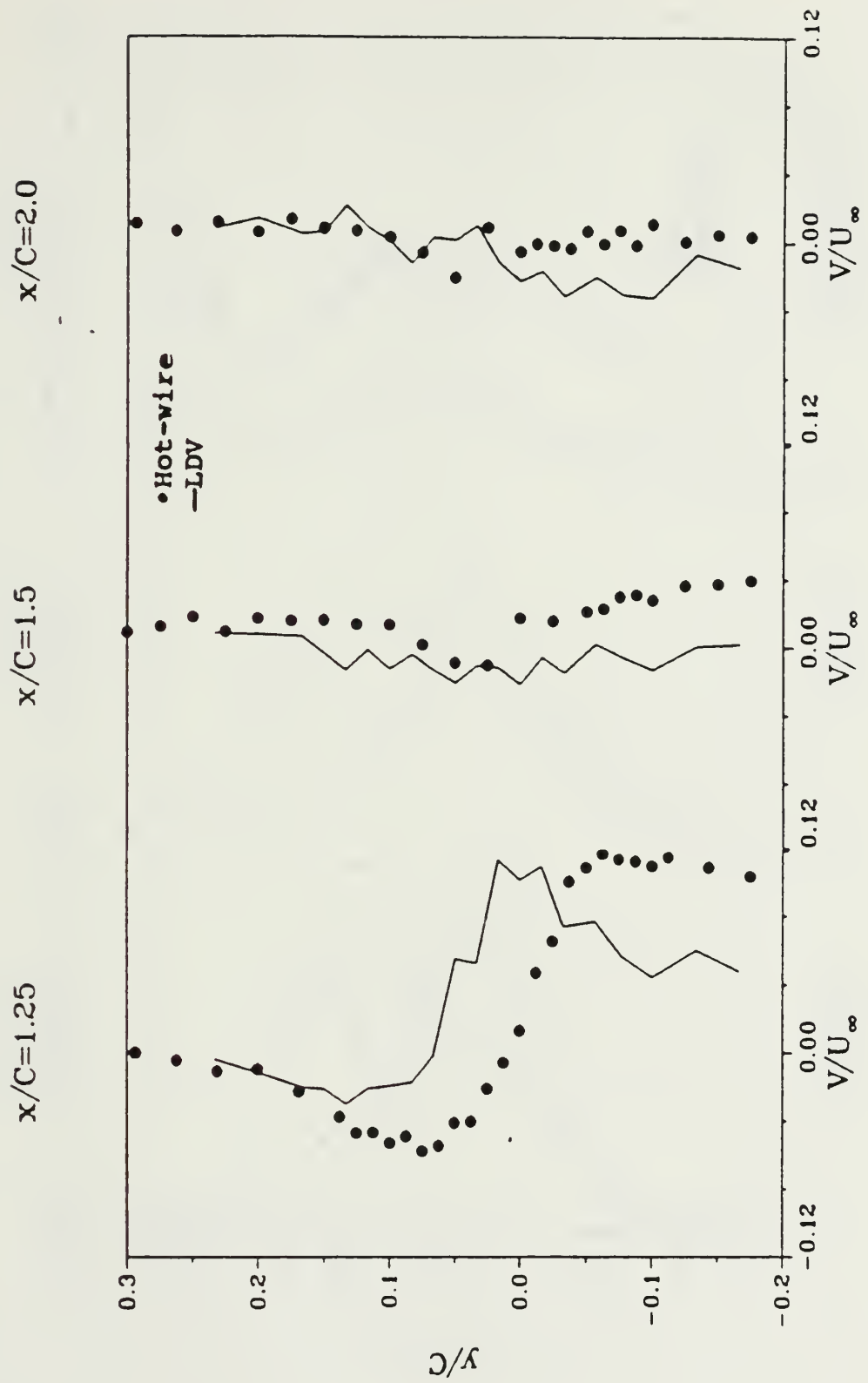
Figure 4.18    Comparison of LDV and hot-wire data for transverse velocity.
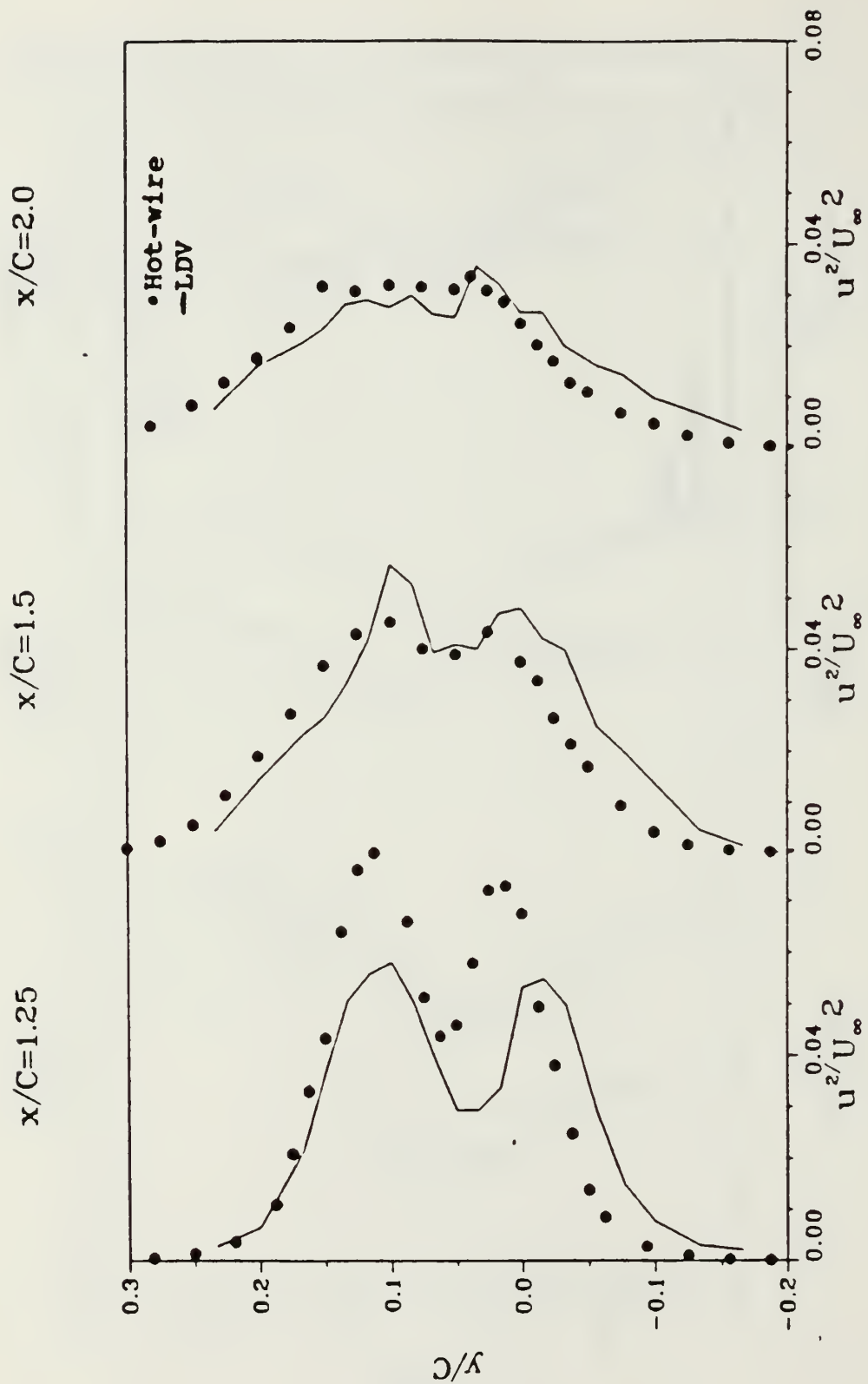
Figure 4.19    Comparison of LDV and hot-wire data for longitudinal turbulence stress.

52
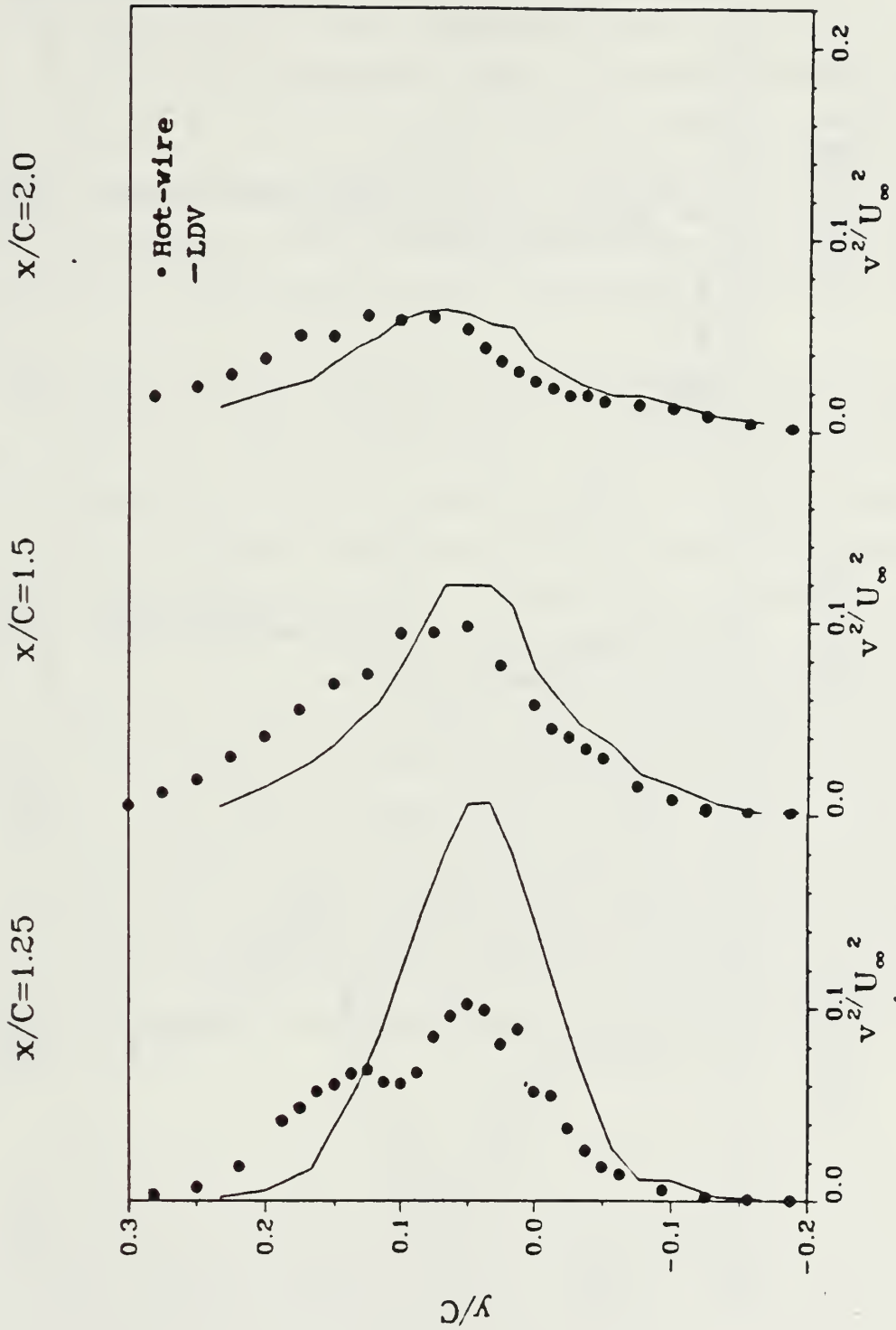
Figure 4.20   Comparison of LDV and hot-wire data for
transverse turbulence stress.

53
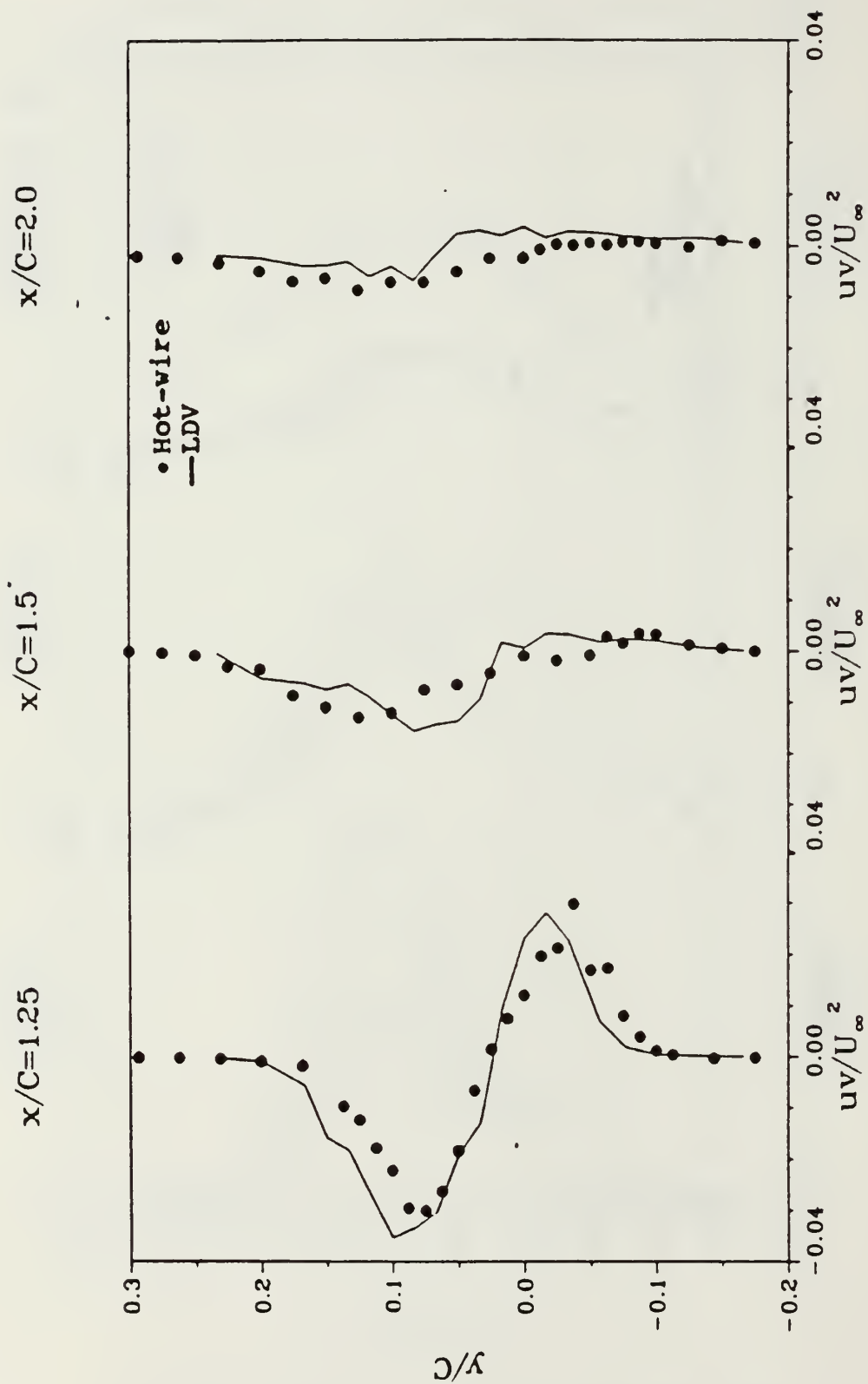
Figure 4.21    Comparison of LDV and hot-wire data for
Reynolds shear stress.

54

## E.    ERROR ANALYSIS

In this experiment, 1000 velocity samples were taken by the LDV in each direction (U and V) at every measurement location. The purpose in taking so many samples was to provide enough values in the fluctuating regions to ensure that an accurate statistical mean could be computed. Consequently, in the data reduction process all 1000 values were averaged to obtain values for $U_{ave}$ and $V_{ave}$ at each location. The equations in Table II were then used to obtain Reynolds shear stress, longitudinal and transverse turbulent stress at these locations (still using all 1000 samples).

To determine its effect, a different data processing method was tested on the raw data from several runs. In this procedure, only the samples which fell within one standard deviation of the mean were considered (approximately 67% of the 1000 samples) in computing $U_{ave}$, $V_{ave}$, $U_{rms}$ and $V_{rms}$. Again the equations in Table II were employed, just as before. This new process had little effect on $U_{ave}$ but $V_{ave}$ changed considerably (from -1.3 to -11.0 at one location tested). However, the $V_{ave}$ values did not always decrease (one location changed from 8.7 to 16.9). Therefore, the changes were not due to the removal of a bias error. The longitudinal and transverse turbulence stress values decreased in all cases. This was expected since the biggest contributors to these values are the velocity terms which differ greatly from the mean.

This new data processing procedure did not improve the data quality by removing any biases (based on the fact that some values of $U_{ave}$ and $V_{ave}$ increased while others decreased on using the new process). As a matter of fact, this process had a negative effect on the data quality in that it neglects velocity extremes which, in turn, lowers the apparent turbulence intensity of the flow field. For this reason, the original data processing procedure (consider all 1000 samples) was used in this experiment.

# V. CONCLUSIONS AND RECOMMENDATIONS

## A. CONCLUSIONS

A two-component LDV system was set up for the purpose of measuring mean and fluctuating quantities of an airfoil with a deflected spoiler. The results of this experiment have shown that this system provides an efficient and effective means of flow field measurement, including regions of reverse flow and large velocity fluctuations. Comparison with hot-wire data demonstrates the LDV's superiority over the hot-wire in measuring in the near wake region.

The results also clearly show two recirculating regions in the wake of the airfoil. One vortex originates at the trailing edge of the airfoil itself while the other originates at the trailing edge of the spoiler. The turbulence region is concentrated in the near wake and dissipates rapidly in the downstream direction.

## B. RECOMMENDATIONS

In order to establish a more complete data base, it is recommended that more LDV measurements be obtained at other than $\alpha = 0°$ and $\delta = 30°$. These results are important to the modeling of this flow field. Also, to remove the possibility of tunnel blockage errors, it is necessary to perform further studies in a large scale wind tunnel.

When using an LDV to measure a turbulent flow field such as in this experiment, a large number of samples should be taken at each location. Furthermore, unless attempting to remove a velocity bias *all* of the samples taken should be considered in computing $U_{ave}$, $V_{ave}$, etc.

# APPENDIX

## COMPUTER PROGRAMS

```
C   PURPOSE - (1) TO CONVERT A 24 HOUR CLOCK TO A 12 HOUR CLOCK.
C           - (2) TO ADD A.M. OR P.M. TO THE "ADJUSTED" TIME.
C
C
        SUBROUTINE STDTM (IDATE,ITIME,IVAL)
        DIMENSION IDATE(3)
        DIMENSION ITIME(3)
        CALL DATE (IDATE,IERROR)
        CALL TIME (ITIME,IERROR)
        IF (ITIME(1).GE.13) GO TO 30
        IF (ITIME(1).EQ.12) GO TO 10
        GO TO 20
   10   IF (ITIME(2).GT.00) GO TO 30
        IF (ITIME(3).GT.00) GO TO 30
   20   IVAL = "AM"
        GO TO 40
   30   IVAL = "PM"
        IF (ITIME(1).LT.13) GO TO 40
        ITIME(1) = ITIME(1) - 12
        GO TO 50
   40   IF (ITIME(1).GE.01) GO TO 50
        ITIME(1) = ITIME(1) + 12
   50   CONTINUE
        RETURN
        END
```

```
C *******************************
C *******************************
C **                          **
C **        SPOILER.FR        **
C **                          **
C **        MIKE FOREMAN      **
C **                          **
C *******************************
C *******************************
C
C LASER DATA ACQUISITION PROGRAM
C
C RLDR SPOILER STDTM D1024 @FLIB@
C
      DIMENSION IFILE(4), IDT(10), VAR(10)
      DIMENSION ITIME(3), IDATE(3)
      DIMENSION IRAY1(1000), IRAY2(1000)
      DIMENSION IBIN1(16), IBIN2(16), VEL1(1000),VEL2(1000)
      DIMENSION V(5,20),X(30),Y(30)
C
C INITIALIZE
C
      DO 10 I=1,3
      IDT(I)=0
      VAR(I)=10.
   10 CONTINUE
C
      ACCEPT "RUN NUMBER (ZERO TO QUIT): ",IRUN
      IF(IRUN.LE.0) GO TO 999
   15 ACCEPT "NUMBER OF SAMPLES PER COMPONENT: ",NUM
      IF(NUM.LE.1000.AND.NUM.GE.0) GO TO 20
      TYPE "NUMBER OF SAMPLES MUST BE BETWEEN 1 AND 1000"
      GO TO 15
   20 ACCEPT "MIXING FREQUENCY #1: ",FREQ1
      ACCEPT "MIXING FREQUENCY #2: ",FREQ2
C
      CON1=16.65
      CON2=16.65
      VAR(1)=CON1
      VAR(2)=CON2
C
C SUBDEVICE ADDRESSES
C
      ISUB1=46K
      ISUB2=47K
C
C TIME PROGRAM
C
      CALL STDTM(IDATE,ITIME,IVAL)
C
      DO 30 I=1,3
      IDT(I)=IDATE(I)
      IDT(I+3)=ITIME(I)
   30 CONTINUE
      IDT(7)=IVAL
      IDT(8)=IRUN
      VAR(9)=FREQ1
      VAR(10)=FREQ2
C
   35 TYPE "WILL THIS BE A :   (1) WAKE PROFILE"
      ACCEPT "                  (2) BOUNDARY LAYER PROFILE ",IPROF
C
      IF(IPROF.EQ.1.OR.IPROF.EQ.2) GO TO 40
      TYPE "MUST ENTER 1 OR 2"
```

```
      GO TO 35
40  IF(IPROF.EQ.2) GO TO 41
    ACCEPT "X-LOCATION FOR THIS RUN (XT/C): ",VAR(3)
    GO TO 42
41  ACCEPT "X-LOCATION FOR THIS RUN (X/C): ",VAR(3)
42  ACCEPT "NUMBER OF Y-LOCATIONS: ",NMAX
    IF(IPROF.EQ.2) GO TO 45
    ACCEPT"STANDARD WAKE PROFILE Y-LOCATIONS? (1=YES,0=NO) ",LL
    IF(LL.EQ.1) GO TO 44
    TYPE"INPUT Y-LOCATIONS IN INCHES (LOWEST POINT FIRST):"
    DO 43 I=1,NMAX
    WRITE (10,49) I
    ACCEPT" ",Y(I)
43  CONTINUE
    GO TO 50
44  Y(1)=-1.0
    Y(2)=-0.8
    Y(3)=-0.6
    Y(4)=-0.46
    Y(5)=-0.34
    Y(6)=-0.2
    Y(7)=-0.1
    Y(8)=0.0
    Y(9)=0.1
    Y(10)=.2
    Y(11)=.3
    Y(12)=.4
    Y(13)=.5
    Y(14)=.6
    Y(15)=.7
    Y(16)=.8
    Y(17)=.9
    Y(18)=1.0
    Y(19)=1.2
    Y(20)=1.4
    GO TO 50
45  TYPE"STANDARD BOUNDARY LAYER PROFILE Y-LOCATIONS? "
    ACCEPT"                    (1=YES, 0=NO): ",LK
    IF(LK.EQ.1)GO TO 47
    TYPE"INPUT Y-LOCATIONS IN INCHES (LOWEST POINT FIRST):"
    DO 46 I=1,NMAX
    WRITE(10,49) I
    ACCEPT" ",Y(I)
46  CONTINUE
    CO TO 50
47  Y(1)=.1
    Y(2)=.2
    Y(3)=.3
    Y(4)=.4
    Y(5)=.5
    Y(6)=.6
    Y(7)=.7
    Y(8)=.8
    Y(9)=.9
    Y(10)=1.0
    Y(11)=1.1
    Y(12)=1.2
    Y(13)=1.3
    Y(14)=1.4
    Y(15)=1.5
49  FORMAT(6X,"Y(",I2,"):")
50  WRITE(10,125)
125 FORMAT(" ","BEGIN (SCANI.FR) >>",Z)
    CALL FSWAP("SCANI.SV")
```

```
               ACCEPT "DO YOU WANT RAW DATA STORED? (1=YES, 0=NO) ",IRAW
               IDT(9)=IRAW
               IDT(10)=IPROF
C
C BEGIN TAKING DATA
C
               N=0
        57 CALL DIO11(ISUB1,IRAY1,IRAY2,NUM,IER)
C
C DECODE
C
               AVE1=0.
               AVE2=0.
        60 DO 90 I=1,NUM
                   DO 65 J=1,16
                   IBIN1(J)=IAND(IRAY1(I),2**(J-1))
                   IBIN2(J)=IAND(IRAY2(I),2**(J-1))
                   IF(IBIN1(J).NE.0) IBIN1(J)=1
                   IF(IBIN2(J).NE.0) IBIN2(J)=1
        65     CONTINUE
               IBN1=0
               IBN2=0
                   DO 70 J=0,9
                   IBN1=IBN1+IBIN1(J+1)*2**J
                   IBN2=IBN2+IBIN2(J+1)*2**J
        70     CONTINUE
               IEXP1=0
               IEXP2=0
                   DO 75 J=10,13
                   IEXP1=IEXP1+IBIN1(J+1)*2**(J-10)
                   IEXP2=IEXP2+IBIN2(J+1)*2**(J-10)
        75     CONTINUE
C
C
               VEL1(I)=CON1*(2.**(5-IEXP1)*1000./FLOAT(IBN1)-40.+FREQ1)
               VEL2(I)=CON2*(2.**(5-IEXP2)*1000./FLOAT(IBN2)-40.+FREQ2)
               AVE1=AVE1+VEL1(I)
               AVE2=AVE2+VEL2(I)
C
        90 CONTINUE
C
               AVE1=AVE1/NUM
               AVE2=AVE2/NUM
C
C CHECK VELOCITIES ARE IN LIMITS
C
               NN=N+1
               WRITE(10,92)NN,AVE2,AVE1
        92 FORMAT(1X,"LOCATION: ",I2,4X,"U(AVE)= ",F9.5,4X,"V(AVE)= ",F9.5)
               IF(AVE1.GT.35.) GO TO 95
               IF(AVE2.GT.140.) GO TO 95
               GO TO 98
        95 WRITE FREE(10) "BAD DATA: LOCATION ",NN
               ACCEPT"RETRY OR SKIP TO NEXT LOCATION? (1=RETRY, 0=SKIP): ",ITRY
               IF(ITRY.EQ.0)GO TO 98
               CALL DIORM
               GO TO 57
C
        98 IF(IRAW.NE.1) GO TO 100
C
C STORE RAW DATA
C
               CALL FOPEN(5,"COUNTER")
               READ BINARY(5) NJ
```

```
          CALL FCLOSE(5)
          NJ=NJ+1
          CALL FOPEN(5,"COUNTER")
          WRITE BINARY(5) NJ
          CALL FCLOSE(5)
          NFILE=NJ
          IF(N.EQ.0) JFILE=NFILE
          IR=MOD(NFILE,10)
          IS=NFILE/100
          IL=(NFILE-IS*100)/10
          IFILE(1)='RA'
          IFILE(2)='WD'
          IFILE(3)=(IS+60K)*400K+(IL+60K)
          IFILE(4)=(IR+60K)*400K
C
          CALL FOPEN(5,IFILE)
          WRITE BINARY(5) (IDT(I),I=1,10)
          WRITE BINARY(5) (VAR(I),I=1,10),NUM,Y(NN)
          WRITE BINARY(5) (IRAY1(I),I=1,NUM)
          WRITE BINARY(5) (IRAY2(I),I=1,NUM)
          CALL FCLOSE(5)
C
  100 WRITE (10,99)
   99 FORMAT(" ","*** BEGIN RMS CALCULATIONS >>",Z)
          URMS=0.
          VRMS=0.
          UVRMS=0.
          DO 110 I=1,NUM
          URMS=URMS+((VEL2(I))**2-(AVE2)**2)
          VRMS=VRMS+((VEL1(I)**2-(AVE1)**2))
          UVRMS=UVRMS+(VEL1(I)*VEL2(I))-(AVE1*AVE2)
  110 CONTINUE
          URMS=(URMS/FLOAT(NUM))
          VRMS=(VRMS/FLOAT(NUM))
          UVRMS=(UVRMS/FLOAT(NUM))
          WRITE (10,111)
  111 FORMAT("+",">> END RMS CALCULATIONS")
          N=N+1
          V(1,N)=AVE2
          V(2,N)=AVE1
          V(3,N)=URMS
          V(4,N)=VRMS
          V(5,N)=UVRMS
          IF(N.GE.NMAX) GO TO 120
C
C MOVE TRAVERSE
C
          CALL FSWAP("TRELAY.SV")
          ACCEPT"TRAVERSE MOVED...ANY NUMBER TO CONTINUE.  ",IAA
C
          CALL DIORM
          GO TO 57
C
C OBTAIN TEMP, STAG PRES., MACH #, ETC
C
  120 IF(IRUN.EQ.1600) GO TO 127
          CALL FSWAP("TRELAY.SV")
          WRITE(10,126)
  126 FORMAT("TRAVERSE RESET TO INITIAL POSITION")
  127 CALL FOPEN(5,"SCANI")
          READ BINARY(5) VAR(4),VAR(5),VAR(6),VAR(7),VAR(8)
          CALL FCLOSE(5)
C
C WRITE DATA INTO PERMANENT DATA FILE
```

```
              CALL FOPEN(5,"PERMCOUNT")
              READ BINARY(5) MF
              CALL FCLOSE(5)
              WRITE FREE(10) "LAST DATA FILE USED: ",MF
              WRITE FREE(10) "RUN NUMBER: ",IRUN
              ACCEPT "'DATA' FILE NUMBER (NEG # TO SKIP): ",MFILE
              IF(MFILE.LT.0) GO TO 599
              CALL FOPEN(5,"PERMCOUNT")
              WRITE BINARY(5) MFILE
              CALL FCLOSE(5)
              IR=MOD(MFILE,10)
              IL=MFILE/10
              IFILE(1)='DA'
              IFILE(2)='TA'
              IFILE(3)=(IL+60K)*400K+(IR+60K)
              IFILE(4)=0
C
              CALL FOPEN(5,IFILE)
              WRITE BINARY(5) (IDT(I),I=1,10)
              WRITE BINARY(5) (VAR(I),I=1,10),NUM,NMAX,JFILE,NFILE
              WRITE BINARY(5) ((V(I,J),J=1,NMAX),I=1,5)
              WRITE BINARY(5) (Y(I),I=1,NMAX)
              CALL FCLOSE(5)
C
         599  WRITE FREE(10) "AMBIENT TEMP:                   ",VAR(4)," DEGF"
              WRITE FREE(10) "ATMOSPHERIC PRESSURE:       ",VAR(5)," PSI"
              WRITE FREE(10) "STAGNATION PRESSURE:        ",VAR(6)," PSI"
              WRITE FREE(10) "FREE STREAM MACH NUMBER: ",VAR(7)
              WRITE FREE (10) "FREE STREAM VELOCITY:       ",VAR(8)," M/S"
              DO 650 I=1,NMAX
              Y(I)=Y(I)/6.
         650  CONTINUE
              ACCEPT"DO YOU DESIRE A CURVE? (1=YES, 0=NO): ",ICURVE
              IF(ICURVE.EQ.0) GO TO 975
              WRITE FREE(10)
         600  TYPE"WHAT PROFILE DO YOU DESIRE?"
              TYPE"        (1) U(AVE)/U(INFINITY)"
              TYPE"        (2) V(AVE)/U(INFINITY)"
              TYPE"        (3) U(RMS)/(U(INFINITY)**2)"
              TYPE"        (4) V(RMS)/(U(INFINITY)**2)"
              ACCEPT"        (5) UV(RMS)/(U(INFINITY)**2)    ",ISEL
              BIGX=0.
              DO 700 I=1,NMAX
              IF(ISEL.LE.2) X(I)=V(ISEL,I)/VAR(8)
              IF(ISEL.GT.2) X(I)=V(ISEL,I)/(VAR(8)**2)
              IF(X(I).GT.BIGX) BIGX=X(I)
         700  CONTINUE
              CALL FOPEN(5,"PROFILE")
              WRITE BINARY(5) NMAX,IPROF,ISEL,BIGX
              WRITE BINARY(5) (X(I),I=1,NMAX)
              WRITE BINARY(5) (Y(I),I=1,NMAX)
              CALL FCLOSE(5)
              CALL FSWAP("PLOTP.SV")
              ACCEPT"ANY # TO CONTINUE ",ANY
              TYPE "DO YOU DESIRE ANOTHER GRAPH? "
              ACCEPT"            (1=YES, 0=NO):    ",IGR
              IF(IGR.EQ.1)GO TO 600
         975  WRITE FREE(10)"ENSURE PRINTER IS ON"
              WRITE(12,980)IDATE,ITIME,IVAL
         980  FORMAT(10X,"DATE: ",2(I2,"/"),I4,5X,"TIME: ",2(I2,":"),I2,1X,A2)
              WRITE FREE(12)
              WRITE FREE(12)"RUN NUMBER: ",IRUN
              WRITE FREE(12)
              IF(IPROF.EQ.1) WRITE FREE(12)"WAKE PROFILE"
```

```
      IF(IPROF.EQ.2) WRITE FREE(12)"BOUNDARY LAYER PROFILE"
      WRITE FREE(12)"   X-LOCATION: ",VAR(3)
      WRITE FREE(12)
      WRITE FREE(12)"NUMBER OF Y-LOCATIONS TAKEN: ",NMAX
      WRITE FREE(12)
      WRITE(12,981)
981   FORMAT(2X,"LOCATION",10X,"U(AVE)",10X,"V(AVE)",10X,"U(RMS)",
     811X,"V(RMS)",11X,"UV(RMS)")
      DO 985 I=1,NMAX
      WRITE(12,984)Y(I),V(1,I),V(2,I),V(3,I),V(4,I),V(5,I)
984   FORMAT(2X,F8.6,9X,F9.4,8X,F9.4,7X,F10.4,7X,F10.4,7X,F10.4)
985   CONTINUE
      WRITE FREE(12)
      WRITE FREE(12)"NUMBER OF SAMPLES PER Y-LOCATION: ",NUM
      WRITE FREE(12)"MIX FREQ #1= ",FREQ1,"  MIX FREQ #2= ",FREQ2
      WRITE FREE(12)"VEL CONST #1= ",CON1,"  VEL CONST #2= ",CON2
      WRITE FREE(12)
      IF(IRAW.EQ.0) WRITE FREE(12)"RAW DATA HAS NOT BEEN STORED"
      IF(IRAW.EQ.1) WRITE FREE(12)"RAW DATA IS STORED IN 'RAWD' FILES ",
     8JFILE," THRU ",NFILE
      WRITE FREE(12)"PERMANENT DATA FILE: DATA",MFILE
      WRITE FREE(12)
      WRITE FREE(12)"AMBIENT TEMP=            ",VAR(4)," DEGF"
      WRITE FREE(12)"ATMOSPHERIC PRESSURE= ",VAR(5)," PSI"
      WRITE FREE(12)"STAGNATION PRESSURE=  ",VAR(6)," PSI"
      WRITE FREE(12)"FREE STREAM MACH #=   ",VAR(7)
      WRITE FREE(12)"FREE STREAM VELOCITY= ",VAR(8)," M/S"
999   STOP
      END
```

63

```
C  ****************************
C  ****************************
C  **                      **
C  **       "SCANI.FR"      **
C  **                      **
C  **       MIKE FOREMAN    **
C  **                      **
C  ****************************
C  ****************************
C
C  "SCANI.FR" TAKES THE DATA FROM THE 6
C  SCANIVALVES AND WRITES THIS DATA (IN COUNTS)
C  ON THE SCREEN AND INTO A DATA FILE.
C
       DIMENSION IRAY(1200), Y(6,0:23)
C
C  THE SCANIVALVES ARE CONNECTED TO CHANNELS 1 THROUGH 6:
C
       NSTART = 1
       LIMIT  = 6
       NUM = LIMIT-NSTART+1
C
C  ZEROIZE THE MATRIX
C
       DO 10 I = 1,6
       DO 10 J = 0,23
       Y(I,J) = 0
   10 CONTINUE
C
C  SCANIVALVE RELAY INFORMATION
C  IDEVICE = DEVICE NUMBER (25K FOR SCANIVALVE)
C  RELAY NUMBERS: HOME = RELAY #3
C                 STEP = RELAY #2
C  TO CONVERT RELAY NUMBER TO BINARY WORD USE:
C      N=2**(16-N)
C
       IDEVICE = 25K
       N1=2          ;STEP = RELAY#2
       ISTEP = 2**(16-N1)
       N2=3          ;HOME = RELAY#3
       IHOME = 2**(16-N2)
C
C  RESET ALL BITS TO ZERO
C
       CALL DOUTW(IDEVICE,0)
C
C  SETUP THE A/D DEVICE WITH THE STARTING AND ENDING CHANNELS
C
       CALL FADST(NSTART,LIMIT,IER)
C
C  RESET THE SCANIVALVE TO THE HOME POSITION
C  (ENERGIZE THE RESPECTIVE RELAY, THEN DEENERGIZE IT)
C
       CALL DOUTW(IDEVICE,IHOME)
       CALL FDELY(5)
       CALL DOUTW(IDEVICE,0)
C
C  TAKE 200 SAMPLES AT EACH PORT
C
       DO 30 L=0,23
       DO 20 N=1,200
       CALL FADCT(IRAY((N-1)*NUM+1),NUM,IER)
   20 CONTINUE
C
```

```
C STEP THE SCANIVALVES TO THE NEXT PORT
C
      CALL DOUTW(IDEVICE,ISTEP)
      CALL FDELY(5)
      CALL DOUTW(IDEVICE,0)
C
C COMPUTE THE TOTAL COUNTS FOR EACH PORT (OF EACH SCANIVALVE)
C AND STORE EACH TOTAL IN THE ARRAY, Y.
C
      DO 30 M=NSTART,LIMIT
      M1=M-NSTART+1
      DO 30 N=1,206
      Y(M1,L)=Y(M1,L)+IRAY((N-1)*NUM+(M-NSTART+1))
   30 CONTINUE
C
C RETURN THE SCANIVALVES TO THE HOME POSITION
C
      CALL DOUTW(IDEVICE,IHOME)
      CALL FDELY(5)
      CALL DOUTW(IDEVICE,0)
C
C DISPLAY THE AVERAGE SCANIVALVE VALUES (IN COUNTS) ON THE SCREEN
C NOTE: THE AVERAGE IS COMPUTED INSIDE THE WRITE STATEMENT ITSELF.
C
C
      WRITE FREE(10)"          BEGIN TEMP.SV..."
      CALL FSWAP("TEMP.SV")
      WRITE FREE(10)"          END TEMP.SV >>> BEGIN CALPRES.SV..."
      CALL FSWAP("CALPRES.SV")
      WRITE FREE(10)"          END CALPRES.SV >>> BEGIN NPARO.SV..."
      CALL FSWAP("NPARO.SV")
      WRITE FREE(10)"          END NPARO.SV >>> CONTINUE SCANI.SV..."
      CALL FOPEN(5,"TEMP")
      READ BINARY(5) TEMP
      CALL FCLOSE(5)
      CALL FOPEN(5,"CALPRES")
      READ BINARY(5) CAL
      CALL FCLOSE(5)
      CALL FOPEN(5,"ATMPRES")
      READ BINARY(5) ATM
      CALL FCLOSE(5)
      ATM=ATM*3377/6895          ;CONVERT TO PSI
      WRITE FREE(10)"CAL",CAL
      TEMPR=TEMP+459.6          ;CONVERT TO RANKINE
      TOTPRES=(Y(1,2)-Y(1,0))*CAL/(Y(1,1)-Y(1,0))+ATM
      STATPRES=(Y(4,2)-Y(4,0))*CAL/(Y(4,1)-Y(4,0))+ATM
      FMACH=SQRT(ABS(5.*(((STATPRES/TOTPRES)**(-2./7.))-1.)))
      TRY1=5.*(((STATPRES/TOTPRES)**(-2./7.))-1.)
      TRY2=ABS(TRY1)
      IF(TRY1.EQ.TRY2) GO TO 40
      WRITE FREE(10)"STATPRES IS GREATER THAN TOTPRES !!"
   40 T1=TEMPR/(1+(FMACH**2.)/5.)
      A=SQRT(1.4*1716.*T1)*.3048
      FVEL=A*FMACH
      CALL FOPEN(5,"SCANI")
      WRITE BINARY(5) TEMP, ATM, TOTPRES, FMACH, FVEL
      CALL FCLOSE(5)
C REMOVE THE DEVICES
C
      CALL DIORM
      CALL FADRM
C
      STOP
      END
```

```
C *************************
C *************************
C **                     **
C **       "TEMP.FR"     **
C **                     **
C **       MIKE FOREMAN  **
C **                     **
C *************************
C *************************
C
C "TEMP.FR" COMPUTES THE CURRENT ATMOSPHERIC
C TEMPERATURE AT THE INLET TO THE INDRAFT
C TUNNEL.  THIS VALUE IS OUTPUT TO THE DISPLAY
C SCREEN AND ALSO WRITTEN INTO A FILE CALLED
C "TEMP".
C
      DIMENSION IRAY(200)
C
C THE TEMPERATURE PROBE INTERFACES WITH CHANNEL 8
C
      NSTART = 8
      LIMIT = 8
      NUM = LIMIT-NSTART+1
C
C SET UP THE DEVICE
C
      CALL FADST(NSTART,LIMIT,IER)
C
C TAKE 200 SAMPLES
C
      DO 10 I=1,200
      CALL FADCT(IRAY(I),NUM,IER)
   10 CONTINUE
C
C COMPUTE THE TOTAL NUMBER OF COUNTS FOR THE 200 SAMPLES
C
      TEMP=0.
      DO 20 I=1,200
      TEMP=TEMP+IRAY(I)
   20 CONTINUE
C
C CALCULATE THE AVERAGE OF THE 200 SAMPLES
C
      TEMP=TEMP/200.
C
C THE TEMPERATURE SIGNAL ENTERS THE AMPLIFIER IN VOLTS.
C THE AMPLIFIER GIVES THE SIGNAL A 60DB GAIN (FACTOR
C OF 1000). THEREFORE, THE SIGNAL GOES TO THE A/D CONVERTER WITH DIMENSIONS
C OF MILLIVOLTS.  AFTER CONVERSION, THE FACTOR 1638.3 COUNTS/MILLIVOLT
C IS NECESSARY TO CONVERT THE COMPUTER UNITS (COUNTS) BACK TO MILLIVOLTS:
C
      TEMP=TEMP/1638.3            ;CONVERT COUNTS BACK TO MILLIVOLTS
C
C THE "TEMP" HAS NOW BEEN CONVERTED TO MILLIVOLTS
C HOWEVER, THE TEMPERATURE EQUATION REQUIRES THAT
C THE "TEMP" BE IN MICROVOLTS:
C
      TEMP=TEMP*1000.
C
C
C BECKMAN COEFFICIENTS
C
      C0=3.1922787E+01
      C1=3.5497620E-02
```

66

```
        C2=-2.4786655E-07
C
C CALCULATE TEMPERATURE
C
        TEMP=C0+C1*TEMP+C2*TEMP**2
C
C WRITE TEMP TO SCREEN AND FILE "TEMP"
C
C       WRITE FREE (10)
        WRITE FREE (10) "TEMPERATURE (DEGF)= ",TEMP
        CALL FOPEN (5,"TEMP")
        WRITE BINARY (5) TEMP
        CALL FCLOSE (5)
C
C DISCONNECT THE DEVICE
C
        CALL FADRM
C
        STOP
        END
```

```
C ****************************
C ****************************
C **                        **
C **        "CALPRES.FR"     **
C **                        **
C **        MIKE FOREMAN     **
C **                        **
C ****************************
C ****************************
C
C "CALPRES.FR"   THIS PROGRAM COMPUTES THE
C CALIBRATED PRESSURE TO THE SCANIVALVES.
C
      DIMENSION IRAY(200)
C
C THE CALIBRATION PRESSURE IS CONNECTED TO CHANNEL 7.
C
      NSTART = 7
      LIMIT = 7
      NUM = LIMIT-NSTART+1
C
C SET UP THE A/D DEVICE:
C
      CALL FADST(NSTART,LIMIT,IER)
C
C TAKE 200 SAMPLES AT CHANNEL 7
C
      DO 10 I=1,200
      CALL FADCT(IRAY(I),NUM,IER)
   10 CONTINUE
C
C COMPUTE THE AVERAGE OF THE 200 SAMPLES
C
      Y=0.
      DO 20 I=1,200
      Y=Y+FLOAT(IRAY(I))
   20 CONTINUE
      Y=Y/200.
C
C CALIBRATION PRESSURE IN INCHES OF HG = VOLTS*10
C
      CAL=(Y/1638.3)*10.
C
C CALIBRATION PRESSURE IN PSI = INCHES OF HG * (3377/6895)
C
      CAL=CAL*(3377./6895.)
C     WRITE FREE(10) CAL
C
C WRITE THE CALIBRATION PRESSURE TO THE SCREEN AND TO
C A TEMPORARY FILE CALLED "CALPRES".
C
C     WRITE FREE(10)
C     WRITE (10,25) CAL
   25 FORMAT ("CALIBRATION PRESSURE: ",F7.4," PSI")
C
      CALL FOPEN (5,"CALPRES")
      WRITE BINARY (5) CAL
      CALL FCLOSE (5)
C
C REMOVE THE DEVICE
C
      CALL FADRM
      STOP
      END
```

```
C "PLOTP.FR" IS CALLED BY "SPOILER.FR" TO PLOT SELECTED VELOCITY
C PROFILES.
C
      DIMENSION X(25), Y(25)
      DIMENSION IST1(3),IST2(8),IST3(8),IST4(8)
      DIMENSION IST5(8),IST6(9),IST7(21),IST8(31)
C
      CALL CHRSIZ(4)
      DATA IST1/89,47,67/
      DATA IST2/85,40,65,86,69,41,47,85/
      DATA IST3/86,40,65,86,69,41,47,85/
      DATA IST4/85,40,82,77,83,41,47,85/
      DATA IST5/86,40,82,77,83,41,47,85/
      DATA IST6/85,86,40,82,77,83,41,47,85/
      DATA IST7/87,65,75,69,32,86,69,76,79,67,73,84,89,32,
     *89,82,79,70,73,76,69/
      DATA IST8/66,79,85,78,68,65,82,89,32,76,65,89,69,82,32,
     *86,69,76,79,67,73,84,89,32,80,82,79,70,73,76,69/
C
      CALL FOPEN(5,"PROFILE")
      READ BINARY(5) NMAX, IPROF, ISEL, BIGX
      READ BINARY(5) (X(I),I=1,NMAX)
      READ BINARY(5) (Y(I),I=1,NMAX)
      CALL FCLOSE(5)
      IF(BIGX.LT..5) BIGX=.5
      WRITE FREE(10)Y(1),Y(NMAX),BIGX
      ACCEPT"ANY NUMBER TO CONTINUE: ",IRAND
C
      CALL INITT(960)
      CALL BINITT
      CALL CHRSIZ(3)
      CALL TERM(3,1023)
      CALL SLIMX(160,900)
      CALL SLIMY(150,650)
      CALL XFRM(5)
      CALL YFRM(5)
      CALL XTICS(10)
      CALL YTICS(10)
      CALL DLIMX(0.0,BIGX)
      CALL DLIMY(Y(1),Y(NMAX))
      CALL NPTS(NMAX)
      CALL CHECK(X,Y)
      CALL DSPLAY(X,Y)
      CALL CHRSIZ(3)
      CALL MOVABS(10,525)
      CALL VLABEL (3,IST1)
      CALL MOVABS(300,725)
      IF(IPROF.EQ.1) CALL HLABEL(21,IST7)
      IF(IPROF.EQ.2) CALL HLABEL(31,IST8)
      CALL MOVABS(420,75)
      IF(ISEL.EQ.1) CALL HLABEL(8,IST2)
      IF(ISEL.EQ.2) CALL HLABEL(8,IST3)
      IF(ISEL.EQ.3) CALL HLABEL(8,IST4)
      IF(ISEL.EQ.4) CALL HLABEL(8,IST5)
      IF(ISEL.EQ.5) CALL HLABEL(9,IST6)
      CALL FINITT(0,750)
      CALL CHRSIZ(4)
      STOP
      END
```

69

```
C *******************************
C *******************************
C **                           **
C **         HISTOGRAM.FR       **
C **                           **
C **         MIKE FOREMAN       **
C **                           **
C *******************************
C *******************************
C
C HISTOGRAM.FR RECORDS DATA FROM THE LDV
C COUNTER AND PLOTS A HISTOGRAM OF THIS DATA.
C
C REQUIRED SUBROUTINES: DIO22 @FLIB@
C
      DIMENSION IRAY(1000),IBIN(16),FREQ(1000)
      DIMENSION X(101),Y(101),VEL(1000)
      TYPE "INPUT SUBDEVICE CODE --- TWO DIGITS ONLY:"
      TYPE "                     CHANNEL 1 = 46"
      TYPE "                     CHANNEL 2 = 47"
      READ(11,5) ISUB
    5 FORMAT(O2)
      ACCEPT "VELOCITY CONSTANT? ",CON
      ACCEPT "MIXING FREQUENCY? ",FREQM
   10 ACCEPT "NUMBER OF SAMPLES (0 TO STOP) ?",NUM
      IF (NUM.GT.1000.OR.NUM.LT.0) GO TO 10
      IF (NUM.EQ.0) GO TO 999
      CALL DIOII(ISUB,IRAY,NUM,IER)
C
      DO 100 J=1,NUM
         DO 50 I=1,16
         IBIN(I)=IAND(IRAY(J),2**(I-1))
   50    IF(IBIN(I).NE.0) IBIN(I)=1
      IBN=0
         DO 60 I=0,9
         IBN=IBN+IBIN(I+1)*2**I
   60    CONTINUE
C
      IEXP=0
         DO 70 I=10,13
         IEXP=IEXP+IBIN(I+1)*2**(I-10)
   70    CONTINUE
C
      FREQ(J)=32000./FLOAT(IBN*2**IEXP)
      VEL(J)=CON*(FREQ(J)-40.+FREQM)
  100 CONTINUE
C
      AVER=0.
      AVE=0.
      DO 110 I=1,NUM
      AVER=AVER+FREQ(I)
      AVE=AVE+VEL(I)
  110 CONTINUE
      AVER=AVER/NUM
      AVE=AVE/NUM
      WRITE FREE(10) "AVERAGE DOPPLER FREQUENCY= ",AVER,"MHZ"
      WRITE FREE(10) "AVERAGE VELOCITY= ",AVE," M/S"
      ACCEPT "DO YOU WISH A HISTOGRAM? (YES=1, NO=0)",AA
      IF(AA.EQ.0) GO TO 999
      MM=IFIX(AVE)
      JJ=MM-5
      IF(JJ.LT.0) JJ=0
      KK=JJ+10
      LL=(JJ*10)-1
```

```
        IW=0
        Z=0.
        DO 200 I=1,101
        K=I+LL
        X(I)=(FLOAT(K))/10.
        Y(I)=0.
            DO 150 J=1,NUM
            II=IFIX(10.*VEL(J))
            IF(II.EQ.K) Y(I)=Y(I)+1
  150       CONTINUE
        WRITE FREE (10) X(I),Y(I)
        IW=IW+IFIX(Y(I))
        IF(Y(I).GT.Z) Z=Y(I)
  200 CONTINUE
        Z=FLOAT((IFIX(Z/100.)*100)+100)
        IF(Z.GT.1000.) Z=1000.
        AB=FLOAT(JJ)
        AC=FLOAT(KK)
        WRITE FREE (10) AB,AC,Z
C
        CALL FOPEN (5,"HISTO")
        WRITE BINARY (5) AB,AC,Z
        WRITE BINARY (5) (X(I), I=1,101)
        WRITE BINARY (5) (Y(I), I=1,101)
        CALL FCLOSE (5)
        CALL FSWAP ("HISTOGRAPH.SV")
        WRITE FREE(10)
        WRITE FREE(10)
        WRITE FREE(10)
        WRITE FREE(10)
        WRITE FREE (10) "            TOTAL SAMPLES PLOTTED: ",IW
        CALL DIORM
  999 STOP
        END
```

71

```
C "HISTOGRAPH.FR"  USED BY HISTOGRAM.FR TO PLOT
C A HISTOGRAM OF LASER DATA.
C
      DIMENSION X(101),Y(101)
      DIMENSION IST1(7), IST2(21), IST3(15)
C
      DATA IST1/83,65,77,80,76,69,83/
      DATA IST2/72,73,83,84,79,71,82,65,77,
     *32,79,70,32,76,68,86,32,68,65,84,65/
      DATA IST3/70,82,69,81,85,69,78,67,89,32,40,77,72,90,41/
C
      CALL FOPEN(5,"HISTO")
      READ BINARY (5) AB,AC,Z
      READ BINARY (5) (X(I),I=1,101)
      READ BINARY (5) (Y(I),I=1,101)
      CALL FCLOSE (5)
C
C
      CALL INITT(960)
      CALL BINITT
      CALL TERM(3,1023)
      CALL VBARST(15,6,3)
      CALL SLIMX(100,900)
      CALL SLIMY(150,650)
      CALL XFRM(2)
      CALL YFRM(5)
      CALL XTICS(10)
      CALL YTICS(10)
      CALL XMTCS(10)
      CALL YMTCS(2)
      CALL DLIMX(AB,AC)
      CALL DLIMY(0.0,Z)
      CALL NPTS(101)
      CALL CHECK(X,Y)
      CALL DSPLAY(X,Y)
      CALL MOVABS(10,525)
      CALL VLABEL(7,IST1)
      CALL MOVABS(350,725)
      CALL HLABEL(21,IST2)
      CALL MOVABS(420,75)
      CALL HLABEL(15,IST3)
      CALL MOVABS(900,150)
      CALL DRWABS(900,650)
      CALL CHRSIZ(4)
      CALL FINITT(0,750)
      STOP
      END
```

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