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CALIBRATION AND APPLICATION OF A COMBINATION TEMPERATURE-PNEUMA--ETC(U)
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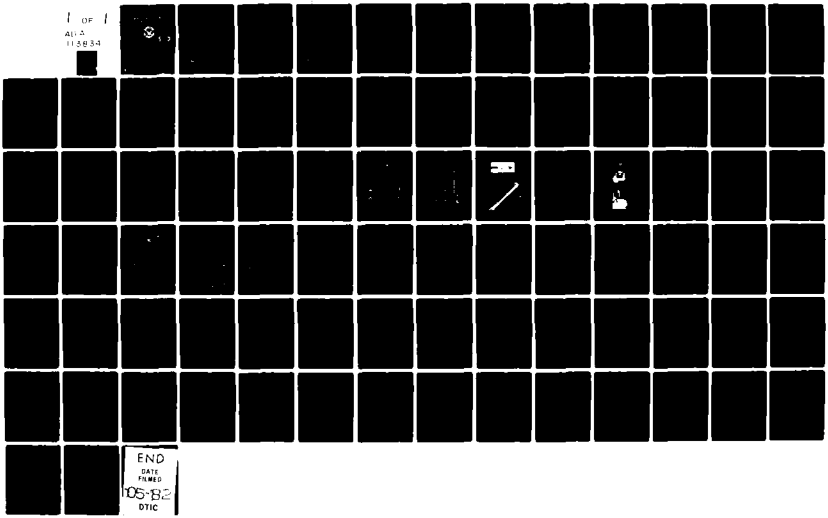

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NPS67-81-03CR

# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



CONTRACTOR REPORT

**CALIBRATION AND APPLICATION OF A COMBINATION TEMPERATURE-PNEUMATIC PROBE FOR VELOCITY AND ROTOR LOSS DISTRIBUTION MEASUREMENTS IN A COMPRESSOR**

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December 1981

Contractor Report

Approved for public release; distribution unlimited

Prepared for:
Naval Postgraduate School
Monterey, California 93940

**NAVAL POSTGRADUATE SCHOOL**
**Monterey, California**



The work reported herein was carried out for the Naval Postgraduate School by BDM Corporation under Work Order 086426, under Contract Number N00014-78-C-0204. The work was part of a program entitled Transonic Compressor Investigations funded in part by Naval Air Systems Command Code AIR-310 and Code AIR-330 under the cognizance of, formerly Dr. H. J. Mueller, currently Dr. G. Heiche.

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Publication of the report does not constitute approval of the sponsor for the findings or conclusions. It is published for information and for the exchange and stimulation of ideas.

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Dean of Research

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER NPS67-81-03CR | 2. GOVT ACCESSION NO. AD-A113 834 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) Calibration and Application of a Combination Temperature-Pneumatic Probe for Velocity and Rotor Loss Distribution Measurements in a Compressor | | 5. TYPE OF REPORT & PERIOD COVERED Contractor Report |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) F. Neuhoff | | 8. CONTRACT OR GRANT NUMBER(s) N00014-78-C-0204 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS BDM Corporation P.O. Box 2019 Monterey, California 93940 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940 | | 12. REPORT DATE December 1981 |
| | | 13. NUMBER OF PAGES |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Interim Report. Principal Investigator, Dr. R. P. Shreeve, Director, Turbopropulsion Laboratory, Naval Postgraduate School, Monterey, California, 93940

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Compressor Measurements

Probe Calibration

Temperature-Pneumatic Probe

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A description is given of the current design of a temperature-pneumatic probe used for radial flow field surveys in an axial compressor. The procedure used to calibrate the probe for variations in Mach number, pitch and yaw angles in a free jet is described and the procedure for representing the characteristics of the probe analytically as three polynomial surfaces, is given.

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S/N 0102-014-6601

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Verification of the calibration in steady flow and application of the probe to obtain radial surveys in a small axial compressor are also described. The procedures developed and reported here allow the probe to be used with automatic reduction of data by mini-computer without the need for iteration.

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# 1. INTRODUCTION

The probe reported here was designed to be used to determine the radial distribution of the time-averaged flow in a small, single-stage axial compressor (Figure 1). While the probe has more general application, the chosen geometry is the result of its first intended application.

The probe was designed to measure air flows in the range of Mach number from 0.3 to 0.7 with pitch angles expected in the range 0 to 15 degrees and stagnation temperatures from atmospheric to about 150$^{o}$F (65$^{o}$C). Static pressure would range from 0.6 to about 1.2 atmospheres.

The prototype of the present probe was built by Dodge and was reported in Ref 1. The first application of the earlier design to measure rotor losses and deviation angles was reported in Ref 2 and Ref 3. In Ref 3, errors in the earlier work were corrected and the method used to analytically represent the calibration of the probe was set out more clearly.

The design of the present probe departs only in detail from that of the prototype, for reasons which are given in Section 2. However, the method now used to represent the calibration of the probe is quite different and considered to be much improved over that reported in earlier references.

In the present report, the probe design is described in Section 2 and the analytical and experimental procedures used in its calibration are given in Section 3. Steady flow tests to verify the calibration and compressor measurements are reported in Section 4 and conclusions are given in Section 5. The analytical basis for the pneumatic calibration representation is given in Appendix A. The computer programs, procedures and data files used in the calibration and verification are given in Appendix B.

# 2. PROBE DESCRIPTION

## 2.1. General Arrangement

The probe is designed to measure four pressures and one temperature. Figure 2 shows a drawing of the probe and a view is shown in Figure 3. Due to the symmetry of the probe about one plane through its (radial) axis, a balancing of the pressures at sensors P2 and P3 in Figure 3 by rotating the probe around the radial axis allows the yaw angle to be read against a vernier scale or recorded using a potentiometer read-out of the angular orientation. The pitch angle as well as the magnitude of the dimensionless velocity (or Mach number) at the probe tip are calculated using the pressure readings of the four sensors. The relationship of the pressures to Mach number and pitch angle must first be established by calibration. The stagnation temperature is needed in order to calculate the magnitude of the velocity from the dimensionless velocity or Mach number. The exposed fine-wire thermocouple sensor supported in the stagnation region formed by a glassy aluminum oxide insulator, gives an output which corresponds fairly closely to stagnation temperature. The departure from stagnation temperature, the recovery factor, must also be established by calibration.

## 2.2. Design Features

The probe was designed to have separate sensors to avoid the so-called "stem-effect" associated with cylindrical probes having surface sensors (Reference 4). The restricted axial gap in the compressor (0.63") did not allow the use of a "goose-neck" conical probe. As was reported in Reference (2), the stem-effect was found to be negligible for the first probe geometry to within 0.25" of the wall. The probe was designed to be translated through a hole of 0.25 inches diameter. The sensors P1, P2 and P3 were placed at the same radial location and therefore similarly average the flow from the upstream rotor blade wakes. These sensors largely dictate the measurement of Mach number. The pressures P1 and P4 largely dictate the measurement of pitch. The sensor P4 was unavoidably displaced radially from the other three. However, since the pitch angle variation to be measured was rather small, and since the radial gradients in flow properties were small outside the wall boundary-layers, this necessity was easily accepted. It is also noted that when the probe is adjusted in yaw, the sensor P1 will indicate stagnation pressure very closely since the pitch angle is not expected to exceed $15^{\circ}$.

The radial separation of the temperature sensor was also easily accepted since the probe was to be translated in radial surveys and the physical displacement could be accounted for in the data reduction. The arrangement and the geometry of the temperature sensor were chosen so that a high recovery factor and sensitivity would be obtained and yet the element could be repaired easily in the event of a failure. The shape ground into the glassy insulator and the method of stringing the thermocouple wire were changed from those reported in References 1 and 3. In the new arrangement, a long length of thermocouple wire is exposed on either side of the junction within the near-stagnation flow ahead of the insulator. This results in a higher recovery factor at all Mach numbers and a more easily controlled and repeatable geometry.

The tubes for sensors P2, P3 and P4 (Figure 3) were oriented at $55^{o}$ to the sensor P1 based on the known behavior of a straight cylindrical tube when pitched or yawed to the flow (Reference 1). An angle of about $55^{o}$ was required in order for the pressure at the sensor to decrease from stagnation to static pressure. In the earlier design (Reference 1) the centers of the sensors were arranged to be on the surface of a small sphere which, in effect, determined the spatial resolution of the probe. This is shown in Figure 4. Also in Figure 4 is shown the tip design of the present probe. The sensors were initially positioned such that the centers of the tubes were aligned in a plane, and were closer together than in the earlier design. Initial tests of the revised geometry resulted in the measurement of small differences between the pressure sensed at P2, P3 and P4, and that at P1. It was conjectured that the surrounding sensors were too nearly aligned with the flow induced over the central sensor and were therefore measuring close to stagnation pressure. The tips of the surrounding sensors were modified as shown in Figure 4 and pressure differences near to dynamic pressure were subsequently obtained.

# 3. CALIBRATION

## 3.1. Apparatus and Procedure

The probe was calibrated in a 4.25" diameter freejet exhausting to atmosphere. The apparatus shown in Figure 5 can be used to establish air flows to a Mach number of unity. Pitch angle can be set within a range of +45 to -45 degrees while the yaw angle can be set to any angle desired. In effecting angle changes the probe tip is rotated about its tip which remains at the same point on the center line of the jet.

The geometry for the tests and the instrumentation are shown in Figure 6. The speed of the flow was adjusted by monitoring the impact pressure using a water manometer board. The static pressure was taken to be the atmospheric pressure while the total pressure and temperature were measured in the air supply pipe immediately upstream of the nozzle. No difference in total pressure was detected in the flow between the sensor upstream of the nozzle to the core of the jet and hence the same total conditions (pressure and temperature) were assumed for the pipe and the jet core. Since the temperature of the supplied air fluctuated measurably due to ambient (coastal) variations, the difference between the total temperature in the pipe and the temperature detected by the combination probe was recorded differentially. A thermocouple probe having a fine-wire sensor similar to that of the combination probe was used at the upstream station. The absolute value of the temperature in the supply air was measured using the same upstream thermocouple element referenced to ice point.

All pressures were converted to voltages using a Scanivalve and single calibrated transducer for which the reference pressure was atmospheric. The thermocouple voltage differences were recorded without amplification. Yaw angles were adjusted to a vernier scale and converted to voltage using a potentiometer. The pitch angle was set to a scale on the adjustable mount and recorded manually.

Pressure tubes P2 and P3 were connected to a U-tube manometer. The probe was aligned (in yaw) with the flow by balancing the two pressures. The pneumatically averaged value of the two pressures - designated P23 - was recorded and used in representing the calibration of the probe. All data were recorded and analyzed using the data acquisition system shown in Figure 7. The programs and organization of data files are given in Appendix B. Before beginning calibration tests, since the sensors for two pressures and the sensor for temperature were physically separated radially, the velocity distribution across the jet was examined. Figure 8 shows the velocity distribution obtained by probe measurement. It can be seen that for a core of approximately 3 inches in diameter the flow was uniform.

The procedure was as follows:

The required Mach number was established. Having allowed some 5 to 10 minutes for the flow to stabilize, the yaw angle of the probe at zero degrees of pitch was checked. With the probe aligned with the flow, P2 and P3 should be the same and the angle read on the vernier scale should be zero. Any departure was corrected by adjusting the probe in the probe holder. The first pitch angle was set at $-6^{\circ}$ and a scan of the data was taken. The pitch angle was changed in increments of $2^{\circ}$ up to an angle of $+18^{\circ}$, taking a data scan at each setting. A sample of the raw data output is shown in Table I.

After one survey over pitch angle, the probe was reset to zero pitch and zero yaw, the Mach number of the flow was changed and the procedure repeated. The range of Mach number from 0.3 to 0.7 was covered in increments of 0.1 or less.

### 3.2. Dimensionless Velocity - Pneumatic Calibration

The characteristics of the probe must be represented such that pressures and temperatures measured in a flow can be related to the pitch and yaw angles and the velocity magnitude. However, since the probe is always rotated to balance the pressures P2 and P3, the yaw angle can always be read directly. It is left therefore to establish the relationship for pitch angle and velocity magnitude in terms of the probe pressures and temperature for the special case of zero yaw.

Appendix A discusses the reduction of the four measured pressures to basically two coefficients:

$$\beta = \frac{P1 - P23}{P1} \tag{1}$$

and

$$\gamma = \frac{P1 - P4}{P1 - P23}, \tag{2}$$

where

$$\delta = \gamma \cdot \beta \tag{3}$$

might be looked at as an alternate choice. These coefficients can be established using the pressure readings from the probe for any flow condition. The calibration gives a total of 104 different values for $\beta$, and corresponding values of $\gamma$ and $\delta$ for 104 separate combinations of Mach number and pitch angle. The reduced data are given in Table II.

It can be argued (Appendix A), and it can be seen in the results that $\beta$ represents largely a measurement of the Mach number and $\gamma$ provides mainly a measurement of the pitch angle. However, if explicit relationships for the reduced velocity, X (defined by Equation A(3) using Equation A(1)), and the pitch angle, $\phi$, in terms of $\beta$ and $\gamma$ can be obtained by representing the calibration data using monotonic mathematical functions, X or $\phi$ can then be determined uniquely for any given values of $\beta$ and $\gamma$. The method involves using mathematical approximations of surfaces which represent the calibration data. In the way that data points which depend on just one variable can be approximated by a polynomial, X and $\phi$ are approximated as being polynomial functions of both $\beta$ and $\gamma$. This leads to mathematical expressions for the calibration surfaces which are of the form:

$$X = \sum_{i=1}^{L} \left\{ \sum_{j=1}^{M} C_{ij} \beta^{(j-1)} \right\} \cdot \gamma^{(i-1)} \tag{4}$$

and

$$\phi = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} D_{ij} \beta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{5}$$

where $C_{ij}$ and $D_{ij}$ are coefficients which must be derived from the data.

Using the computer programs given in Reference 5, the surfaces represented by Equation (4) and Equation (5) were derived from the calibration data. Also derived and examined were the alternate surfaces obtained by electing to use the coefficients $\delta$ and $\gamma$ instead of $\beta$ and $\gamma$, related through Equation (3). The equations for the alternate surfaces are the following:

$$X = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} C_{ij} \delta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{4a}$$

$$\phi = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} D_{ij} \delta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{5a}$$

[It is noted that the representation achieved using Equation (4) and Equation (5) or Equation (4a) and Equation (5a) is similar to the earlier method of polynomial approximation described in Reference 3. However, in the method of Reference 3, the expression for X was implicit and an iterative technique was required to obtain X and $\phi$ from measured values of $\beta$ and $\gamma$ or $\delta$ and $\gamma$. The derivation of the polynomial coefficients using matrix operations makes possible the use of explicit relations for both X and $\phi$.]

The choice of using Equation (4) and Equation (5) or Equation (4a) and Equation (5a) was made after an examination of the relative accuracy of the two methods. Using the calibration data, for each given pair of values for $\delta$ and $\gamma$, X and $\phi$ were calculated using the coefficients determined in the two sets of equations. The calculated X was compared in each case to the actual value set in the calibration test and an error was defined as follows:

$$\varepsilon_X = \frac{X_0 - X_c}{X_0} \cdot 100 \qquad (6)$$

where $X_0$ is the actual value in the calibration test and $X_c$ is the value calculated using the surface approximation equation. The error in X so defined is then a percentage deviation from the actual value. For the pitch angle, the error as a percentage is not meaningful (for example, when $\phi \approx 0$). The error was defined as

$$\varepsilon_\phi = \phi_0 - \phi_c \qquad (7)$$

where $\phi_0$ is the actual value set in the calibration test and $\phi_c$ is the value of the pitch angle (in degrees) calculated using the derived surface approximation equation. From an examination of the relative errors, the selection of using Equation (4a) and Equation (5a), rather that Equation (4) and Equation (5), was made.

The "surfaces" obtained by drawing straight lines between data points on a 3D plot of the test data are shown in Figures 9 and 10 together with the "surfaces" obtained by joining the points calculated using Equation (4a) and Equation (5a). The magnitude of the errors shown graphically in Figure 9 are given in Table

III, together with the values of the coefficients used in the approximation equations.

In the method given in Reference 5 the order of the polynomial approximation can be changed between 1 and 6 for the dependence on $\delta$ and between 1 and 6 for the dependence on $\gamma$, independently. The plots of Figure 9 and the corresponding errors in Table III are for the selection which gave the best results in that the averaged error was least in the range of velocity and pitch angle anticipated in the probe application. As indicated in Table III, the range expected in Mach number is from .3 to .7 and in pitch angle, from $0.0^{\circ}$ to $12.0^{\circ}$. The maximum error within this range was +1.109% in X and $0.417^{\circ}$ in pitch angle, while the average error was -0.061% in X and $-0.016^{\circ}$ in pitch angle.

## 3.3. Temperature Recovery Calibration

Since the probe was to be used to measure losses, requiring an evaluation of velocity magnitude rather than simply the Mach number or dimensionless velocity, it was also required to measure the local flow total temperature.

Even in a flow in which the angle of the velocity vector is uniform and known it is difficult to design a probe which will measure true stagnation temperature to an acceptable accuracy when the Mach number is in the higher subsonic range. In the present design, advantage was taken of the fine wire sensor being small and in poor thermal contact with a glassy insulator. While the "temperature recovery" of the probe was expected to be comparatively high, a calibration to establish the value of the temperature recovery factor was required nevertheless. In the calibration test a voltage was recorded as the result of the temperature difference between the combination probe sensor and the total temperature sensor in the pipe upstream of the jet nozzle. (The relation between the output in millivolts and the temperature in degrees Fahrenheit for a single sensor referenced to ice point is given in Appendix C.) The output of the upstream probe was also recorded with reference to ice point. As the upstream probe was always in a low Mach number flow (less than 0.2), it was assumed that its output corresponded to the total temperature of the flow. The voltage difference between the upstream probe and the combination probe was then a measure of the departure of the combination probe temperature from the stagnation temperature.

The "temperature recovery factor", R, is defined as

$$R = \frac{T_p - T_s}{T_t - T_s} \qquad (8)$$

where $T_p$ is the temperature indicated by the probe, $T_s$ is the static temperature, and $T_t$ is the total temperature of the flow.

Since Equation (8) contains the static as well as the total temperature, one of the two can be expressed in terms of the other and the Mach number or dimensionless velocity. Using Equation A(4) and rearranging, Equation (8) becomes

$$T_t = \frac{T_p}{1 - X^2 + X^2 R} \qquad (9)$$

where X is the velocity made dimensionless by dividing by the "limiting" or "stagnation" velocity defined by Equation A(1). Since X is established by applying the calibration in Section 3.2 to the pneumatic measurements, it is only necessary to know R in order to determine $T_t$ from the temperature $T_p$ indicated by the probe. From the physical arrangement of the probe it is evident that the thermocouple junction is differently exposed to the flow at different yaw and pitch angles, and the Mach number is known to have a major influence on the temperature recovery factor. However, since the yaw angle is always adjusted to zero and the pitch angle and Mach number depend uniquely on the measured values of $\delta$ and $\gamma$, the recovery factor can also be approximated as a surface of values depending on $\delta$ and $\gamma$; thus

$$R = \sum_{i=1}^{L} \left\{ \sum_{j=1}^{M} E_{ij} \delta^{(j-1)} \right\} \cdot \gamma^{(i-1)} \qquad (10)$$

The calibration surface obtained from the calibration test data is shown in Figure 11. The coefficients evaluated from the data and the resulting percentage errors in the approximation are given in Table IV. It can be seen that errors of less than 0.8% occur within the range of measurements.

# 4. APPLICATION

## 4.1. Verification of the Calibration

Before using the probe for compressor measurements, the probe was mounted on the free jet again to obtain data with which to verify the calibration. The probe was aligned with the flow but Mach number and pitch angle were set remotely and unknown to the operator. A total of 12 separate conditions with various combinations of pitch angle and Mach number were set. The results are shown in Table V. The largest error was found to be $0.55^{\circ}$ in pitch and 0.7% in Mach number.

## 4.2. Compressor Measurements

The probe can be used in any flow for which conditions are within the ranges of pitch angle and Mach number covered in the calibration. Its intended application, however, was to determine the flow between blade rows in the compressor shown in Figure 1. In the compressor annulus, large radial gradients might be expected to occur (under some operating conditions) in pitch angle, yaw angle and Mach number, so that account had to be taken of the physical separation (0.08 inches) of the probe pressure and temperature sensors in the radial direction. This could be done easily since the probe was to be used in radial surveys and spatial interpolation could be used in reducing the data.

The procedure adopted was to first interpolate the raw data obtained for the radial distribution of the temperature rise. The data, in the form of the differential voltage between the probe thermocouple sensor and a similar reference thermocouple sensor in the compressor inlet, was interpolated using an overlapping quadratic technique to obtain the differential voltage at the locations at which pneumatic data were taken. The temperature recovery factor was evaluated at each location using Equation 10 using the locally measured values of $\delta$ and $\gamma$. The probe temperature $T_p$ was obtained using the measured value of the reference temperature, the interpolated differential voltage and the thermocouple calibration given in Appendix C. The stagnation temperature was obtained using Equation 9.

An example of the radial distribution of the temperature rise across the rotor measured in this way is shown in Figure 12. The corresponding data are given in Table VI.

The uncertainties in the measurements made in the compressor flow field are similar to the uncertainties present in the probe calibration measurements, since the instrumentation used was the same. However, the calibration was carried out in a uniform steady flow whereas the flow field at the rotor exit is periodic, therefore unsteady. The possible error resulting from unsteady effects is discussed in Appendix D. For the data presented here the possible error due to unsteady effects is negligible. A further evaluation of unsteady effects must be made for measurements made at higher rotational speeds and flow Mach numbers.

## 5. CONCLUSIONS

The combination probe and the method used to represent its calibration which are described in this report represent significant improvements over the prototype probe design and calibration method reported earlier. The pneumatic characteristics of the probe were improved as a result of modifications to the tip geometry. This allowed the pneumatic characteristics to be well represented by a polynomial surface approximation.

The polynomial surface approximation technique used to represent both the pneumatic and temperature characteristics of the probe provides a simpler and more accurate technique than was previously available. Most importantly, however, it allows the calibration to be applied directly, allowing Mach number and pitch angle to be calculated from pressure measurements without the need for iteration.

The improved probe and procedures were well proven in tests carried out in the compressor.

SCANIVALVE # 2

| PORT | VOLTAGE(UNCORR.) |
|---|---|
| 2 | -0.000002 |
| 4 | 0.001355 |
| 6 | 0.000766 |
| 8 | 0.000128 |
| 10 | -0.000240 |
| 12 | 0.000765 |

SCANNER # 1

| CHAN | DATA |
|---|---|
| 25 | 0.003009 |

SCANNER # 2

| CHAN | DATA |
|---|---|
| 6 | 0.002009 |
| 7 | 0.002427 |
| 8 | -0.000004 |

SCANIVALVE # 2

RAW DATA WITH VOLTAGE CORRECTED TO PRESSURES(IN.H2O)

| PA-PA | PCAL-PA** | P1-PA | P23-PA | P4-PA | PK-PA | P BARO (INCH HG) |
|---|---|---|---|---|---|---|
| -0.2000 | 135.500 ** | 76.6000 | 12.8000 | -24.0000 | 76.500 | 30.094 |
| 0.0000 | 135.600 ** | 77.1000 | 13.6000 | -19.0000 | 76.600 | 30.084 |
| -0.4000 | 135.400 ** | 76.5000 | 13.9000 | -14.6000 | 75.900 | 30.167 |
| -0.2000 | 135.400 ** | 76.6000 | 13.9000 | -9.5000 | 76.200 | 30.111 |
| -0.4000 | 135.400 ** | 76.6000 | 13.6000 | -4.4000 | 76.300 | 30.080 |
| -0.4000 | 135.400 ** | 76.3000 | 13.6000 | 1.3000 | 76.400 | 30.131 |
| -0.6000 | 135.200 ** | 76.5000 | 13.3000 | 6.1000 | 76.300 | 30.113 |
| -0.3000 | 135.400 ** | 76.7000 | 13.2000 | 11.2000 | 76.500 | 30.061 |
| -0.7000 | 135.100 ** | 76.1000 | 12.6000 | 15.6000 | 75.900 | 30.046 |
| -0.6000 | 135.100 ** | 76.1000 | 12.4000 | 20.2000 | 76.400 | 30.108 |
| -0.7000 | 135.000 ** | 76.2000 | 12.1000 | 23.9000 | 76.000 | 30.094 |
| -0.7000 | 135.100 ** | 76.1000 | 12.1000 | 27.5000 | 76.500 | 30.142 |
| -0.7000 | 135.100 ** | 75.6000 | 12.0000 | 30.2000 | 75.700 | 30.165 |

RAW DATA CORRECTED TO READINGS IN MILLIVOLTS

| T TUNNEL | T PIPE(IP) | D T(PIPE-COMB) | ** PHI |
|---|---|---|---|
| 2.0087 | 2.4266 | -0.0037 | -6.0000 |
| 2.0092 | 2.4283 | -0.0085 | -4.0000 |
| 2.0063 | 2.4258 | -0.0041 | -2.0000 |
| 2.0083 | 2.4288 | -0.0052 | 0.0000 |
| 2.0098 | 2.4290 | -0.0022 | 2.0000 |
| 2.0072 | 2.4273 | -0.0044 | 4.0000 |
| 2.0101 | 2.4301 | -0.0090 | 6.0000 |
| 2.0128 | 2.4312 | -0.0076 | 8.0000 |
| 2.0119 | 2.4304 | -0.0082 | 10.0000 |
| 2.0080 | 2.4277 | -0.0056 | 12.0000 |
| 2.0089 | 2.4294 | -0.0109 | 14.0000 |
| 2.0091 | 2.4283 | -0.0073 | 16.0000 |
| 2.0105 | 2.4284 | -0.0143 | 18.0000 |

DATA STORED IN YPRB50

**Table I. Example of Calibration Raw Data and Stored Data**

| Beta | Gamma | Delta | X vel | Machno. | Phi | T Tunnel | T ref pipe | Tcomborebe | Rec.Fac |
|---|---|---|---|---|---|---|---|---|---|
| .053425 | 1.521552 | .081288 | .133252 | .300642 | -6.000000 | 96.246826 | 98.163193 | [illegible] | [illegible] |
| .052952 | 1.460870 | .077356 | .132766 | .299525 | -4.000000 | 96.163483 | 98.204239 | 99.092934 | .998678 |
| .052722 | 1.397380 | .073672 | .132033 | .297843 | -2.000000 | 96.285034 | 98.189590 | 98.107498 | .991564 |
| .052722 | 1.318777 | .069528 | .132766 | .299525 | 0.000000 | 96.390561 | 98.137498 | 97.972626 | .986290 |
| .052479 | 1.254386 | .065829 | .132766 | .299525 | 2.000000 | 96.236404 | 98.171997 | 97.966751 | .979139 |
| .052722 | 1.170305 | .061700 | .132522 | .298966 | 4.000000 | 96.257248 | 98.242355 | 98.066467 | .982059 |
| .052709 | 1.100437 | .058003 | .132522 | .298966 | 6.000000 | 96.271133 | 98.236481 | 98.154404 | .991628 |
| .053363 | 1.025862 | .054743 | .132522 | .298966 | 8.000000 | 96.267670 | 98.300980 | 98.239426 | .993722 |
| .052940 | .952174 | .050408 | .132278 | .298404 | 10.000000 | 96.305878 | 98.163193 | 97.957962 | .978986 |
| .053194 | .874459 | .046516 | .132766 | .299525 | 12.000000 | 96.264191 | 98.204239 | 98.107913 | .980037 |
| .053860 | .803412 | .043272 | .133009 | .300083 | 14.000000 | 96.201691 | 98.230621 | 98.259949 | 1.002970 |
| .054078 | .753191 | .040731 | .133252 | .300642 | 16.000000 | 96.232941 | 98.095779 | 97.937454 | .984023 |
| .053885 | .700855 | .037766 | .132766 | .299525 | 18.000000 | 96.208618 | 98.125092 | 97.931580 | .980330 |

| Beta | Gamma | Delta | X vel | Machno. | Phi | T Tunnel | T ref pipe | Tcomborebe | Rec.Fac |
|---|---|---|---|---|---|---|---|---|---|
| .089321 | 1.535627 | .137164 | .176351 | .400612 | -6.000000 | 96.990005 | 98.913498 | 95.592697 | .908953 |
| .088185 | 1.487562 | .131181 | .176867 | .401822 | -4.000000 | 97.167114 | 99.083435 | 95.968597 | .821900 |
| .088166 | 1.420398 | .125231 | .176867 | .401822 | -2.000000 | 97.365067 | 99.270950 | 94.390930 | .721063 |
| .088366 | 1.359802 | .120160 | .176179 | .400208 | 0.000000 | 97.479660 | 99.402740 | 94.296875 | .705939 |
| .088347 | 1.277915 | .112900 | .176523 | .401015 | 2.000000 | 97.712341 | 99.546265 | 95.016922 | .740226 |
| .088785 | 1.192716 | .105008 | .176523 | .401015 | 4.000000 | 97.854721 | 99.745392 | 94.894009 | .675909 |
| .088605 | 1.103961 | .097816 | .176695 | .401419 | 6.000000 | 98.004059 | 99.967941 | 94.623123 | .694283 |
| .089462 | 1.012255 | .090559 | .176867 | .401822 | 8.000000 | 98.160324 | 100.099700 | 95.378281 | .730528 |
| .089662 | .951100 | .085278 | .176523 | .401015 | 10.000000 | 98.361755 | 100.330960 | 95.069809 | .699677 |
| .089521 | .872547 | .078112 | .176695 | .401419 | 12.000000 | 98.600322 | 100.597310 | 96.649658 | .774453 |
| .089980 | .809756 | .072862 | .176006 | .399803 | 14.000000 | 98.677780 | 100.693860 | 95.636749 | .708847 |
| .089760 | .762836 | .068472 | .177038 | .402224 | 16.000000 | 98.966019 | 100.386980 | 96.226959 | .734920 |
| .090630 | .709443 | .064303 | .176006 | .399803 | 18.000000 | 99.341080 | 101.305340 | 94.573166 | .612831 |

| Beta | Gamma | Delta | X vel | Machno. | Phi | T Tunnel | T ref pipe | Tcomborebe | Rec.Fac |
|---|---|---|---|---|---|---|---|---|---|
| .120498 | 1.560976 | .188094 | .207722 | .474838 | -6.000000 | 101.869280 | 103.920810 | 103.564580 | .985360 |
| .118843 | 1.507067 | .179105 | .208549 | .476815 | -4.000000 | 101.949140 | 103.827360 | 103.666780 | .993452 |
| .117164 | 1.448028 | .169656 | .207860 | .475169 | -2.000000 | 101.883160 | 103.941240 | 103.856570 | .996525 |
| .117559 | 1.375000 | .161643 | .207998 | .475498 | 0.000000 | 101.997770 | 103.973360 | 103.754360 | .991025 |
| .118164 | 1.289521 | .152375 | .207860 | .475169 | 2.000000 | 102.011660 | 103.976260 | 103.789410 | .992332 |
| .118189 | 1.197158 | .141490 | .207998 | .475498 | 4.000000 | 102.091520 | 104.090130 | 103.914950 | .992822 |
| .118818 | 1.116608 | .132673 | .207860 | .475169 | 6.000000 | 102.161000 | 104.040500 | 103.827360 | .991254 |
| .119053 | 1.029982 | .122623 | .207584 | .474508 | 8.000000 | 102.150560 | 104.063840 | 103.891620 | .992914 |
| .119658 | .954386 | .114200 | .208136 | .475827 | 10.000000 | 102.202650 | 104.125150 | 103.841960 | .988412 |
| .120338 | .877836 | .105637 | .207998 | .475498 | 12.000000 | 102.216550 | 104.087200 | 103.900380 | .992344 |
| .120918 | .812500 | .098246 | .208412 | .476486 | 14.000000 | 102.157520 | 104.139740 | 104.005460 | .994520 |
| .120918 | .760417 | .091948 | .207860 | .475169 | 16.000000 | 102.275590 | 104.116410 | 103.777740 | .986105 |
| .120309 | .713707 | .085932 | .208274 | .476157 | 18.000000 | 102.250220 | 104.119310 | 103.827360 | .988069 |

| Beta | Gamma | Delta | X vel | Machno. | Phi | T Tunnel | T ref pipe | Tcomborebe | Rec.Fac |
|---|---|---|---|---|---|---|---|---|---|
| .131612 | 1.576802 | .207526 | .219159 | .502265 | -6.000000 | 102.372820 | 104.256500 | 104.148510 | .996016 |
| .130912 | 1.513346 | .198121 | .219031 | .501957 | -4.000000 | 102.390200 | 104.306120 | 104.058000 | .990835 |
| .129110 | 1.455272 | .187890 | .218646 | .501030 | -2.000000 | 102.389470 | 104.233140 | 104.113460 | .995563 |
| .129343 | 1.373206 | .177615 | .218774 | .501339 | 0.000000 | 102.358930 | 104.320710 | 104.168950 | .994381 |
| .129908 | 1.285714 | .167025 | .219159 | .502265 | 2.000000 | 102.411030 | 104.326550 | 104.233140 | .996554 |
| .129370 | 1.196172 | .154748 | .219287 | .502573 | 4.000000 | 102.320720 | 104.276930 | 104.148510 | .995267 |
| .130294 | 1.113924 | .145137 | .219415 | .502880 | 6.000000 | 102.421450 | 104.358660 | 104.095960 | .990331 |
| .130939 | 1.031496 | .135063 | .219287 | .502573 | 8.000000 | 102.515210 | 104.390760 | 104.168950 | .991827 |
| .130993 | .952756 | .124805 | .218903 | .501648 | 10.000000 | 102.483950 | 104.367420 | 104.128050 | .991149 |
| .131433 | .877551 | .115339 | .219543 | .503188 | 12.000000 | 102.348510 | 104.288600 | 104.125150 | .993990 |
| .132204 | .815913 | .107867 | .219159 | .502265 | 14.000000 | 102.379780 | 104.338240 | 104.020870 | .988262 |
| .132025 | .759375 | .100256 | .219798 | .503803 | 16.000000 | 102.386720 | 104.306120 | 104.093050 | .992184 |
| .131335 | .713837 | .093752 | .218774 | .501339 | 18.000000 | 102.435330 | 104.309050 | 103.891620 | .984545 |

Table II. Complete Set of Reduced Calibration Data

| Beta | Gamma | Delta | X vel | Mnchno. | Phi | T Tunnel | T ref pipe | Tcombprobe | Rec.Fac |
|---|---|---|---|---|---|---|---|---|---|
| .153507 | 1.595331 | .244894 | .240619 | .554328 | -6.000000 | 102.793050 | 104.682590 | 104.533770 | .995448 |
| .151745 | 1.538058 | .233393 | .240285 | .553511 | -4.000000 | 103.084750 | 105.015200 | 104.334320 | .994455 |
| .150401 | 1.473545 | .221622 | .240397 | .553783 | -2.000000 | 103.140300 | 105.158140 | 105.050200 | .996695 |
| .149744 | 1.394422 | .208807 | .240619 | .554329 | 0.000000 | 103.296590 | 105.070630 | 104.799560 | .991439 |
| .150291 | 1.300662 | .195478 | .240508 | .554055 | 2.000000 | 103.282700 | 105.149380 | 104.822660 | .990086 |
| .150719 | 1.208719 | .182177 | .240174 | .553238 | 4.000000 | 103.275740 | 105.073530 | 104.816800 | .992124 |
| .151715 | 1.119424 | .169833 | .240731 | .554600 | 6.000000 | 103.286160 | 105.286480 | 105.108550 | .994548 |
| .152329 | 1.043081 | .158892 | .240397 | .553783 | 8.000000 | 103.293120 | 105.268970 | 105.143540 | .996161 |
| .152451 | .959530 | .146281 | .240285 | .553511 | 10.000000 | 103.442460 | 105.341890 | 105.155210 | .994281 |
| .153247 | .884416 | .135534 | .239950 | .552692 | 12.000000 | 103.244510 | 105.315640 | 105.076460 | .992652 |
| .153537 | .822309 | .126255 | .240397 | .553783 | 14.000000 | 103.414670 | 105.336060 | 105.228150 | .996697 |
| .153507 | .767834 | .117868 | .240285 | .553510 | 16.000000 | 103.432020 | 105.403140 | 105.190230 | .993478 |
| .153123 | .714844 | .109459 | .239839 | .552419 | 18.000000 | 103.494540 | 105.394390 | 105.058960 | .989686 |
| **Beta** | **Gamma** | **Delta** | **X vel** | **Mnchno.** | **Phi** | **T Tunnel** | **T ref pipe** | **Tcombprobe** | **Rec.Fac** |
| .173006 | 1.609131 | .278389 | .258473 | .598294 | -6.000000 | 103.852230 | 105.840530 | 105.677250 | .995681 |
| .171937 | 1.550336 | .266560 | .258869 | .599277 | -4.000000 | 104.015460 | 106.012530 | 105.788060 | .994082 |
| .168925 | 1.484055 | .250694 | .258770 | .599031 | -2.000000 | 104.126570 | 106.167020 | 105.960050 | .994541 |
| .167226 | 1.411968 | .236117 | .257677 | .596320 | 0.000000 | 104.140470 | 106.164110 | 106.041690 | .996743 |
| .168445 | 1.315420 | .221577 | .258572 | .598540 | 2.000000 | 104.189090 | 106.172050 | 106.062100 | .997074 |
| .169023 | 1.217540 | .205792 | .258473 | .598294 | 4.000000 | 104.334950 | 106.324420 | 106.263210 | .998382 |
| .170305 | 1.126554 | .191857 | .257876 | .596814 | 6.000000 | 104.345370 | 106.295270 | 106.164110 | .994517 |
| .170497 | 1.040533 | .178772 | .257677 | .596320 | 8.000000 | 104.328000 | 106.382710 | 106.094150 | .992327 |
| .170469 | .967232 | .164003 | .257876 | .596814 | 10.000000 | 104.432190 | 106.414760 | 106.190340 | .994042 |
| .171751 | .890134 | .152001 | .258572 | .598539 | 12.000000 | 104.470380 | 106.478080 | 106.175700 | .991997 |
| .172328 | .823464 | .141906 | .258770 | .599031 | 14.000000 | 104.459980 | 106.473050 | 106.274870 | .994775 |
| .172361 | .773184 | .133267 | .258671 | .598786 | 16.000000 | 104.567630 | 106.615830 | 106.560470 | .998540 |
| .172235 | .717002 | .123493 | .257976 | .597061 | 18.000000 | 104.612700 | 106.674120 | 106.338990 | .991114 |
| **Beta** | **Gamma** | **Delta** | **X vel** | **Mnchno.** | **Phi** | **T Tunnel** | **T ref pipe** | **Tcombprobe** | **Rec.Fac** |
| .194665 | 1.641706 | .319582 | .279619 | .651225 | -6.000000 | 105.776150 | 107.836200 | 107.821620 | .999672 |
| .191932 | 1.583654 | .303954 | .279533 | .651006 | -4.000000 | 105.960270 | 107.914810 | 107.798360 | .997376 |
| .191324 | 1.506256 | .288183 | .279793 | .651463 | -2.000000 | 105.970630 | 108.034150 | 107.943920 | .997971 |
| .189419 | 1.427875 | .270466 | .279706 | .651444 | 0.000000 | 106.203310 | 108.066180 | 107.874050 | .995677 |
| .191124 | 1.329150 | .254032 | .279880 | .651883 | 2.000000 | 106.241520 | 108.156400 | 107.978840 | .996010 |
| .191159 | 1.232625 | .235627 | .278923 | .649467 | 4.000000 | 106.335280 | 108.261180 | 107.958470 | .993153 |
| .190684 | 1.146035 | .218531 | .279359 | .650566 | 6.000000 | 106.380430 | 108.406690 | 108.106900 | .993242 |
| .190860 | 1.058027 | .201935 | .278662 | .648806 | 8.000000 | 106.488080 | 108.363040 | 108.185500 | .995977 |
| .192160 | .973129 | .186994 | .278574 | .649585 | 10.000000 | 106.581850 | 108.604570 | 108.415420 | .995713 |
| .192600 | .897510 | .172860 | .279098 | .649907 | 12.000000 | 106.585330 | 108.688950 | 108.403790 | .993563 |
| .193409 | .835874 | .161646 | .279793 | .651463 | 14.000000 | 106.620060 | 108.735470 | 108.432880 | .993204 |
| .193438 | .779370 | .150760 | .278662 | .648806 | 16.000000 | 106.734660 | 108.758760 | 108.496900 | .994071 |
| .194993 | .732004 | .142736 | .280139 | .652539 | 18.000000 | 106.866620 | 108.782040 | 108.520190 | .994134 |
| **Beta** | **Gamma** | **Delta** | **X vel** | **Mnchno.** | **Phi** | **T Tunnel** | **T ref pipe** | **Tcombprobe** | **Rec.Fac** |
| .217339 | 1.654221 | .359526 | .300115 | .703508 | -6.000000 | 107.561170 | 109.584760 | 109.483000 | .998016 |
| .213911 | 1.596867 | .341588 | .300573 | .704686 | -4.000000 | 107.762590 | 109.799910 | 109.683610 | .997741 |
| .210524 | 1.530151 | .322133 | .300420 | .704294 | -2.000000 | 107.877200 | 109.991760 | 110.032460 | 1.000791 |
| .208658 | 1.444632 | .301434 | .299734 | .702525 | 0.000000 | 107.773010 | 110.003390 | 109.849320 | .996991 |
| .212254 | 1.349627 | .286464 | .300420 | .704294 | 2.000000 | 108.085570 | 110.317930 | 109.773740 | .995253 |
| .210802 | 1.247492 | .262974 | .299351 | .701538 | 4.000000 | 108.148090 | 110.166150 | 109.924910 | .995278 |
| .210208 | 1.156040 | .243009 | .299734 | .702525 | 6.000000 | 108.259200 | 110.247530 | 109.983050 | .994838 |
| .210208 | 1.072148 | .225374 | .299197 | .701144 | 8.000000 | 108.172390 | 110.349240 | 110.087690 | .994877 |
| .210644 | .981559 | .206760 | .299581 | .702131 | 10.000000 | 108.460630 | 110.378300 | 110.177780 | .996083 |
| .212185 | .901912 | .191372 | .300039 | .703312 | 12.000000 | 108.530080 | 110.570080 | 110.320180 | .995135 |
| .212827 | .839967 | .178768 | .300039 | .703311 | 14.000000 | 108.648160 | 110.581700 | 110.360870 | .995701 |
| .214403 | .781250 | .167502 | .299504 | .701933 | 16.000000 | 108.651630 | 110.700820 | 110.384110 | .993813 |
| .214390 | .724076 | .155406 | .299010 | .702721 | 18.000000 | 108.880840 | 110.892560 | 110.642700 | .995131 |

Table II (Cont'd). Complete Set of Reduced Calibration Data

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOX::28

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | .073424 | 3.193492 | -3.328469 | 48.710213 |
| 2 | .055790 | -2.348127 | -14.044533 | -48.302086 |
| 3 | -.157956 | 1.903296 | 14.359398 | 13.222536 |
| 4 | .076260 | -.838803 | -2.848467 | -1.069147 |
| | 1 | 2 | 3 | 4 |

ERRORS(%) AT EACH POINT

Mach # ↓ Pitch # →

| Mach # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1.123 | -.634 | -.502 | .554 | 1.109 | .882 | .898 | .081 | .084 | -.097 | -.759 | -.821 | -.924 |
| 2 | .110 | .706 | .446 | -.129 | .149 | .014 | .334 | -.019 | -.264 | .100 | -.303 | .742 | .172 |
| 3 | -.291 | .275 | .401 | .122 | -.178 | .038 | -.207 | -.351 | -.278 | -.485 | -.248 | -.093 | .905 |
| 4 | .039 | -.508 | -.220 | -.401 | -.371 | .108 | -.116 | -.377 | -.494 | -.230 | -.470 | .347 | .727 |
| 5 | .138 | -.075 | .093 | .351 | .257 | .179 | .168 | -.156 | -.211 | -.562 | -.262 | .083 | .646 |
| 6 | -.237 | -.546 | .136 | .291 | .398 | .437 | -.100 | -.198 | -.101 | -.244 | -.170 | .105 | .491 |
| 7 | .350 | .104 | -.319 | .214 | -.095 | -.121 | .406 | .165 | -.332 | -.250 | -.119 | -.193 | .266 |
| 8 | .027 | -.134 | .103 | .202 | -.705 | -.197 | .378 | .298 | .303 | -.010 | -.034 | -.372 | .391 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOP::28

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 52.538452 | 126.896670 | 232.935610 | 1219 634300 |
| 2 | -69.122833 | -369.909970 | -845.455930 | -1152.339800 |
| 3 | 33.816833 | 370.705320 | 736.521000 | -117.727780 |
| 4 | -8.974613 | -121.604030 | -154.774540 | 186.470580 |
| | 1 | 2 | 3 | 4 |

ABSOLUTE ERRORS AT EACH POINT

Mach # ↓ Pitch # →

| Mach # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -.170 | -.094 | .036 | -.136 | .166 | -.012 | .175 | .190 | .148 | -.135 | -.364 | -.033 | .139 |
| 2 | -.328 | .109 | .090 | .417 | .314 | -.032 | .029 | -.327 | .008 | -.278 | -.251 | .185 | .298 |
| 3 | -.238 | -.009 | .251 | .265 | .155 | .005 | .119 | -.004 | -.002 | -.207 | -.260 | -.018 | .314 |
| 4 | .002 | -.136 | .168 | -.018 | -.117 | -.143 | -.035 | -.030 | -.093 | -.257 | -.195 | -.109 | .253 |
| 5 | -.029 | .049 | .141 | .080 | -.107 | -.115 | -.090 | .122 | -.016 | -.155 | -.097 | .061 | .141 |
| 6 | -.198 | -.176 | -.055 | .125 | -.088 | -.156 | -.105 | .116 | .074 | -.101 | -.186 | .108 | .061 |
| 7 | .222 | .270 | -.036 | .019 | -.181 | -.136 | .099 | .158 | .053 | -.054 | .033 | .126 | .309 |
| 8 | -.167 | .004 | .126 | .010 | -.107 | -.104 | .081 | .278 | .083 | -.131 | -.051 | -.059 | -.131 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |

TABLE III. Pneumatic Calibration Coefficients and Errors in Surface Approximation of Calibration Test Data

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOR

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | .967377 | -.443312 | -1.249223 | 37.673103 | -191.830080 | 813.623660 |
| 2 | .029453 | 1.236710 | -1.544683 | -41.071510 | -43.770836 | -339.013060 |
| 3 | .040476 | -1.567321 | 7.522577 | 28.097572 | 38.016373 | -145.301360 |
| 4 | -.119724 | .257648 | -1.990074 | -8.393269 | 28.396744 | -10.002936 |
| 5 | .104485 | -.078570 | -3.395687 | 12.758770 | 2.119871 | 18.219982 |
| 6 | -.035093 | .251334 | .301610 | -4.679673 | -3.011747 | 1.296416 |
| | 1 | 2 | 3 | 4 | 5 | 6 |

ERRORS(%) AT EACH POINT

Mach # ↓ Pitch # →

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .047 | -.049 | .394 | -.026 | -.710 | -.397 | .561 | .747 | -.765 | -.661 | 1.657 | -.207 | -.576 |
| 2 | -.591 | .084 | .395 | -.140 | .013 | .080 | -.075 | .105 | -.326 | .125 | .418 | -.345 | -.047 |
| 3 | .400 | -.233 | .221 | .104 | .436 | .226 | -.271 | -.111 | -.146 | .200 | -.303 | .196 | -.471 |
| 4 | .236 | .008 | .188 | -.331 | -.446 | -.215 | .030 | .188 | .021 | -.093 | .392 | .170 | -.082 |
| 5 | .016 | -.232 | -.164 | .115 | .222 | .388 | .195 | -.245 | -.076 | -.253 | .097 | .560 | -.050 |
| 6 | .139 | -.110 | .022 | -.070 | .111 | -.108 | -.107 | .123 | .056 | -.164 | -.164 | .001 | .190 |
| 7 | .009 | -.100 | .235 | -.002 | -.046 | .069 | .042 | -.009 | .050 | -.076 | .000 | -.131 | .117 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |

Table IV. Temperature Calibration Coefficients and Errors in Surface Approximation of Calibration Test Data

| Point # [ ] | Beta [ ] | Gamma [ ] | Delta [ ] | Pitch Angle | | | Mach Number | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Actual [°] | Calculated [°] | Error [°] | Actual [ ] | Calculated [ ] | Error [%] |
| 1 | .04203 | 1.36313 | .05730 | - 2.0 | - 2.185 | +0.185 | .2578 | .2579 | -0.07 |
| 2 | .06167 | 1.36059 | .08390 | - 2.0 | - 1.946 | -0.054 | .3220 | .3201 | 0.59 |
| 3 | .06141 | 1.14552 | .07035 | 5.0 | 5.299 | +0.299 | .3210 | .3213 | -0.09 |
| 4 | .07789 | 1.15274 | .08979 | 5.0 | 5.265 | +0.265 | .3660 | .3684 | -0.66 |
| 5 | .08614 | .97416 | .08392 | 10.0 | 9.749 | -0.251 | .3840 | .3866 | -0.67 |
| 6 | .08340 | 1.23467 | .10297 | 3.0 | 2.787 | -0.213 | .3848 | .3838 | 0.27 |
| 7 | .08385 | 1.16711 | .09786 | 5.0 | 4.889 | -0.111 | .3848 | .3845 | 0.09 |
| 8 | .09485 | 1.17783 | .11172 | 5.0 | 4.681 | -0.319 | .4134 | .4125 | 0.22 |
| 9 | .09567 | 1.33638 | .12785 | 0.0 | - 0.425 | +0.425 | .4145 | .4131 | 0.34 |
| 10 | .11626 | 1.21533 | .14129 | 4.0 | 3.822 | +0.178 | .4667 | .4634 | 0.71 |
| 11 | .12066 | .91740 | .11069 | 12.0 | 12.550 | -0.550 | .4678 | .4681 | -0.05 |
| 12 | .14510 | 1.05626 | .15327 | 8.0 | 8.419 | -0.419 | .5258 | .52398 | 0.35 |

Table V. Probe Calibration Verification Test Results

| Normalized Displacement | Yaw | Pitch Angle (Degrees) | Mach Number | $X=V/V_T$ | $T_{total}$ (2) | $T_{total}$ (ref) | Velocity (ft/sec) |
|---|---|---|---|---|---|---|---|
| .092105 | 37.7 | 10.6 | .36928 | .16294 | 96.163651 | 70.670853 | 429.64 |
| .155789 | 38.1 | 9.9 | .37749 | .16646 | 96.340683 | 72.337265 | 416.84 |
| .217368 | 37.4 | 9.1 | .36567 | .16139 | 94.938721 | 71.385300 | 403.05 |
| .271579 | 36.8 | 7.6 | .35321 | .15603 | 94.003922 | 70.343277 | 397.77 |
| .321053 | 35.9 | 6.7 | .34868 | .15407 | 93.712097 | 69.687836 | 393.27 |
| .365789 | 35.1 | 5.9 | .34469 | .15235 | 93.917160 | 70.194351 | 389.52 |
| .423158 | 35.3 | 4.7 | .34132 | .15090 | 94.706573 | 70.760193 | 389.53 |
| .472105 | 34.9 | 4.2 | .34116 | .15083 | 96.342072 | 72.694092 | 388.36 |
| .518421 | 34.6 | 4.0 | .33990 | .15028 | 96.021194 | 73.021072 | 386.09 |
| .589474 | 34.5 | 3.5 | .33777 | .14936 | 95.787674 | 73.347977 | 383.95 |
| .658421 | 33.1 | 3.1 | .33588 | .14854 | 95.057907 | 72.694092 | 381.15 |
| .727895 | 32.7 | 2.7 | .33335 | .14745 | 96.021820 | 73.615387 | 377.52 |
| .797895 | 31.0 | 1.9 | .33013 | .14605 | 99.315994 | 76.256638 | 375.31 |
| .850526 | 31.1 | 1.6 | .32824 | .14524 | 97.394363 | 74.239090 | 375.74 |
| .896842 | 31.2 | 3.0 | .32851 | .14536 | 94.125595 | 71.623383 | 376.15 |
| .947895 | 34.0 | 5.9 | .31257 | .13844 | 92.896500 | 71.385300 | 376.93 |

Table VI. Compressor Test Results

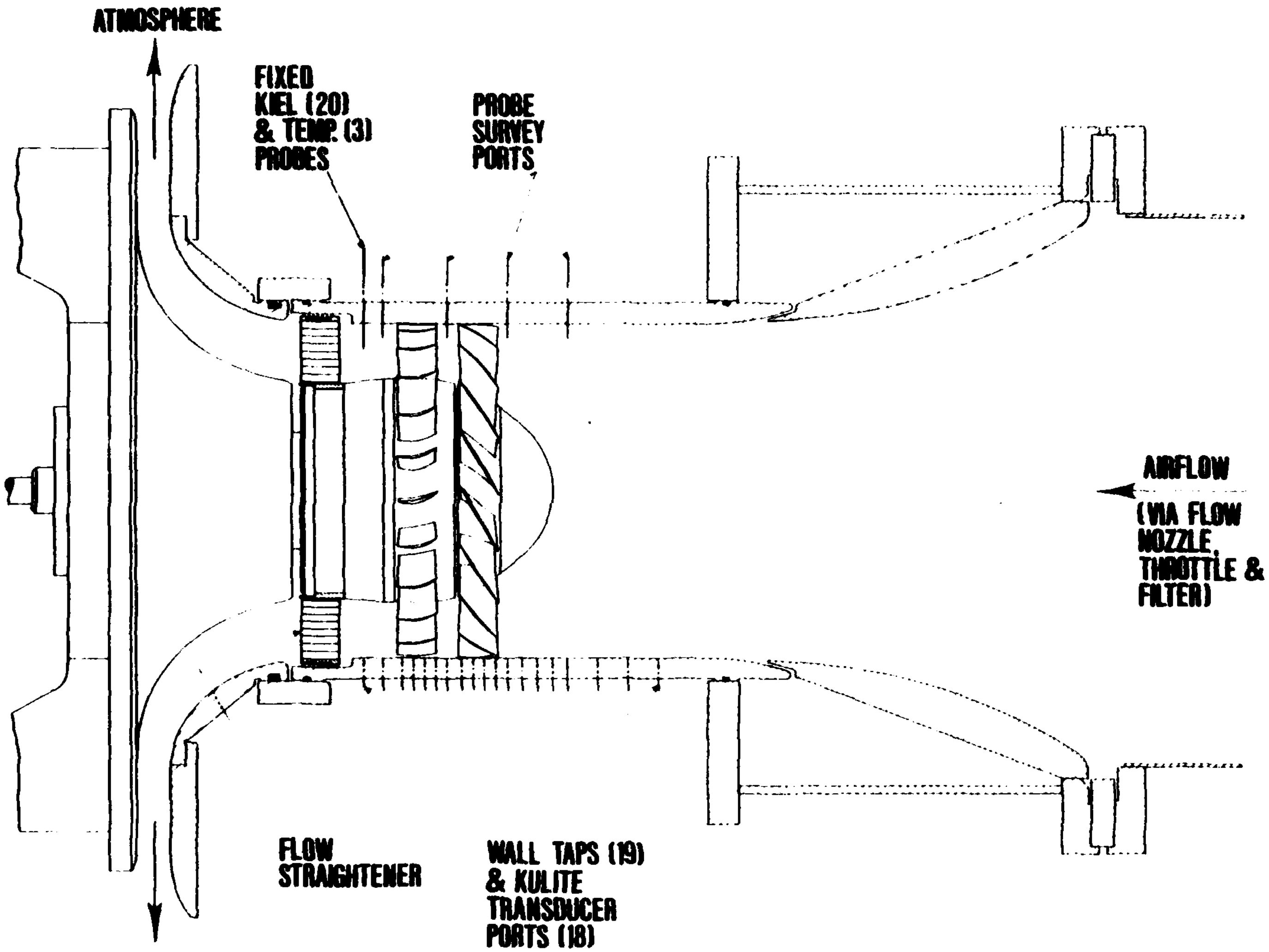



Figure 1. Transonic Compressor

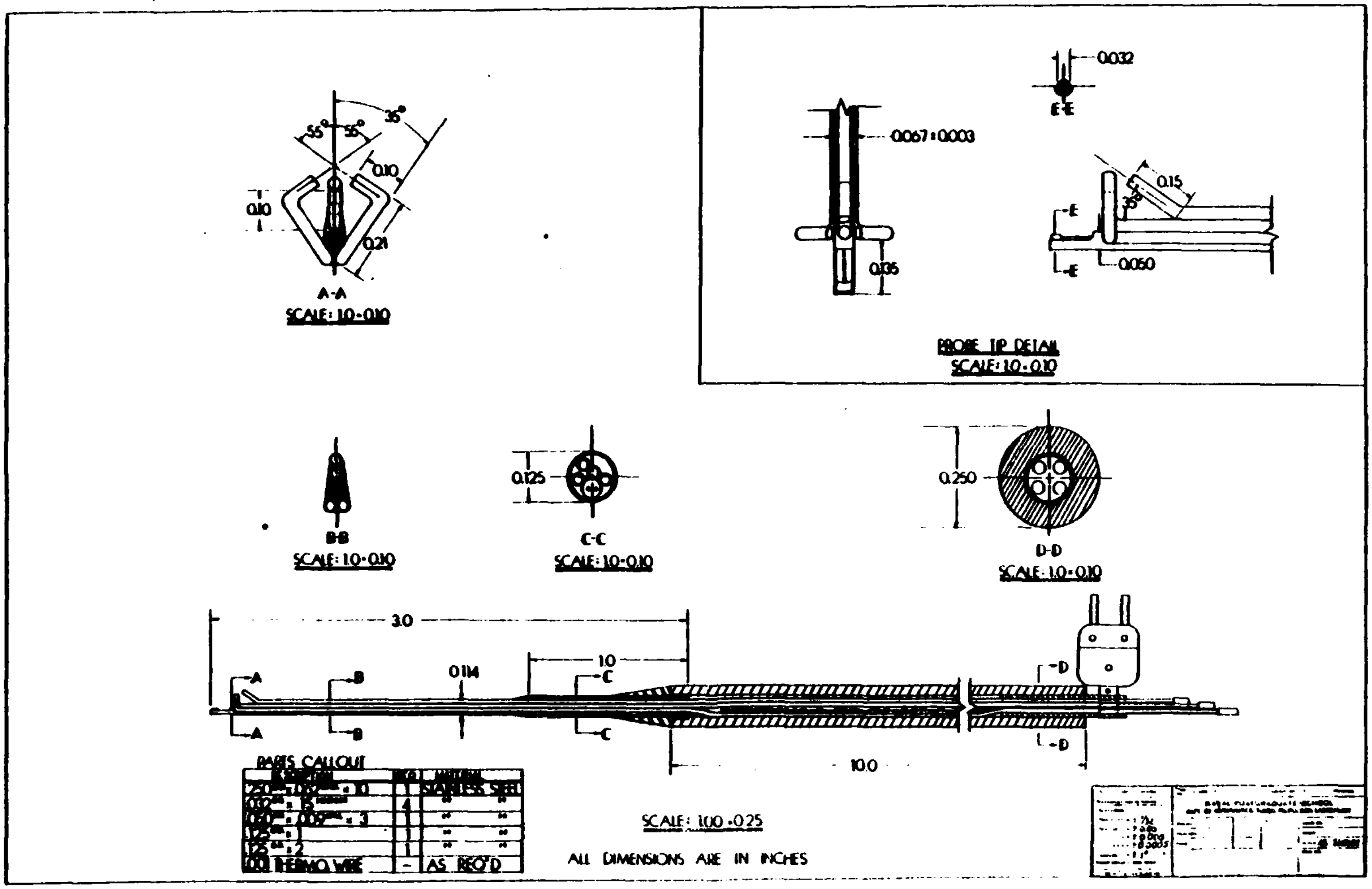
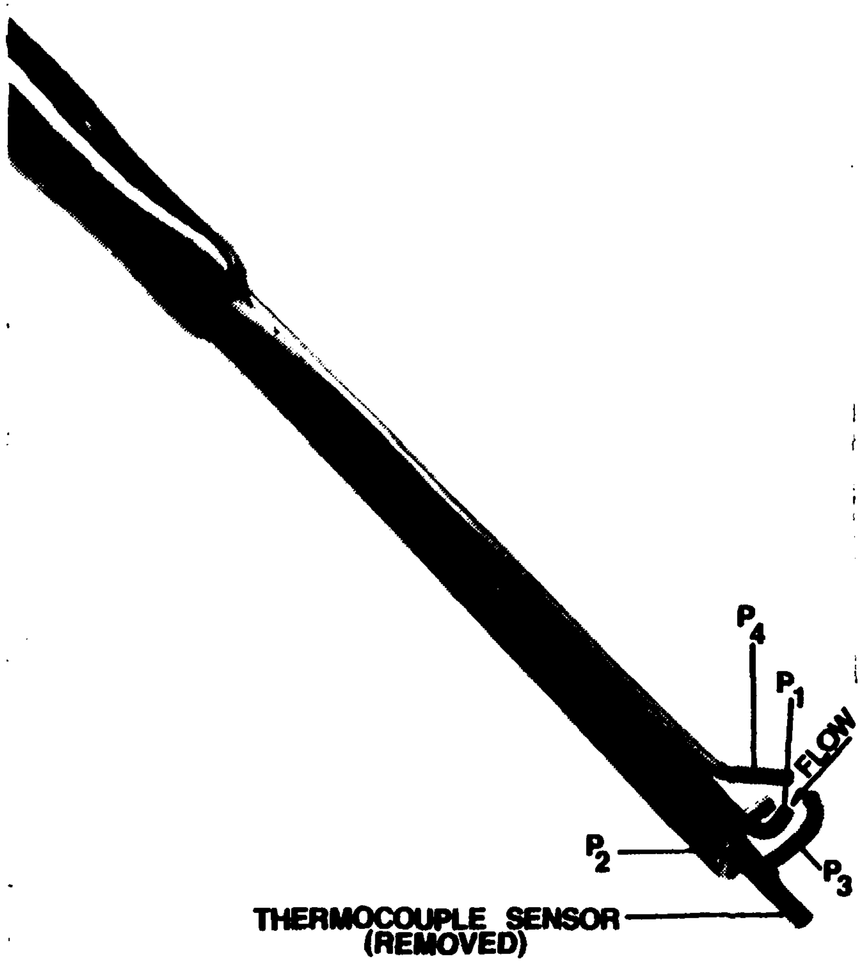
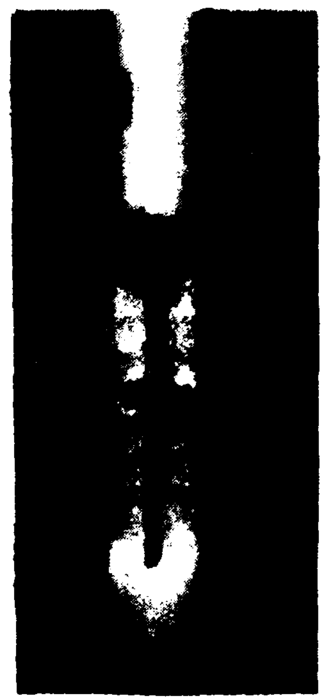



Figure 2. Geometry of the Combination Probe



Scale 20X

Figure 3. Views of the Combination Probe
(Left - With Thermocouple Sensor Removed. Right - Thermocouple Sensor)

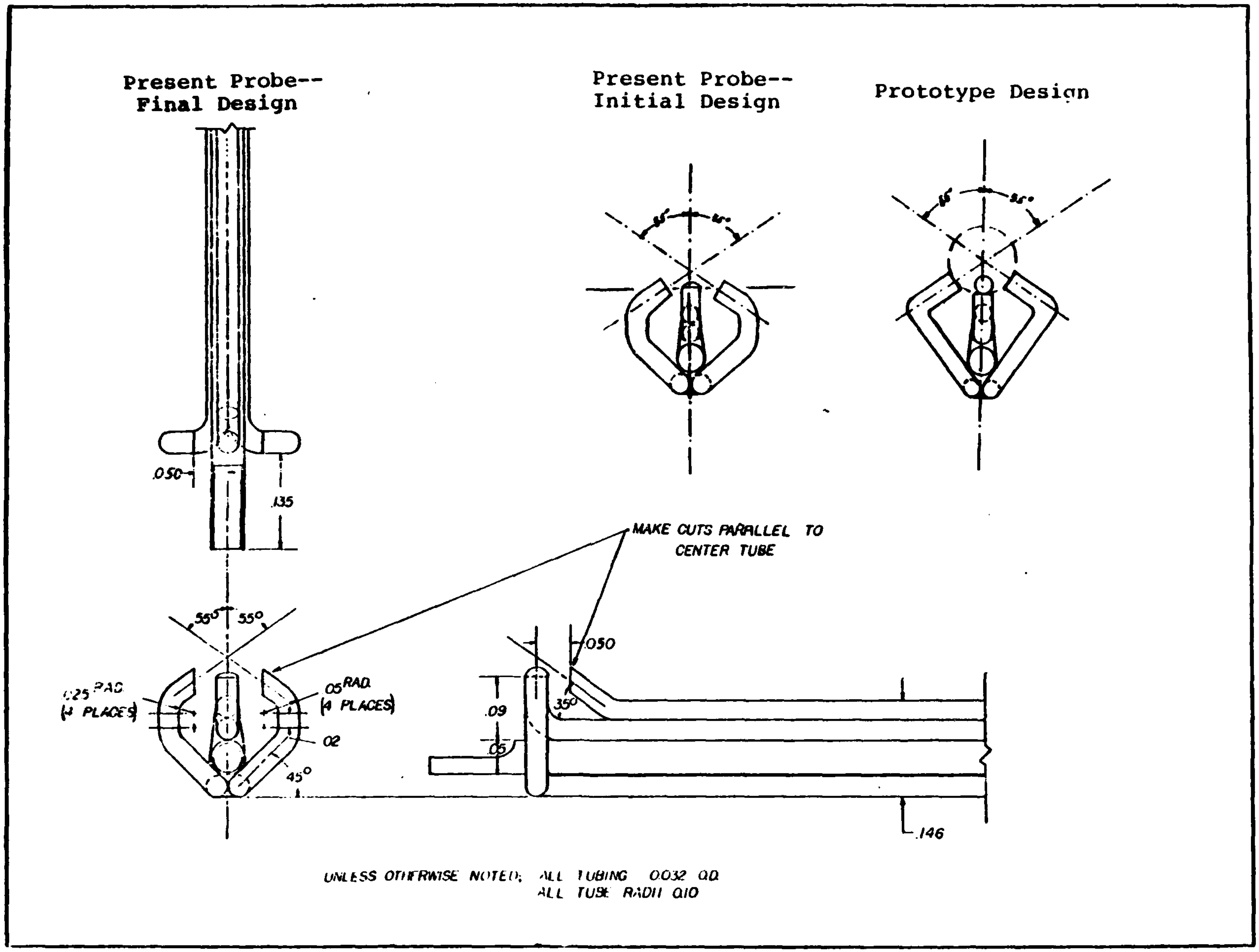
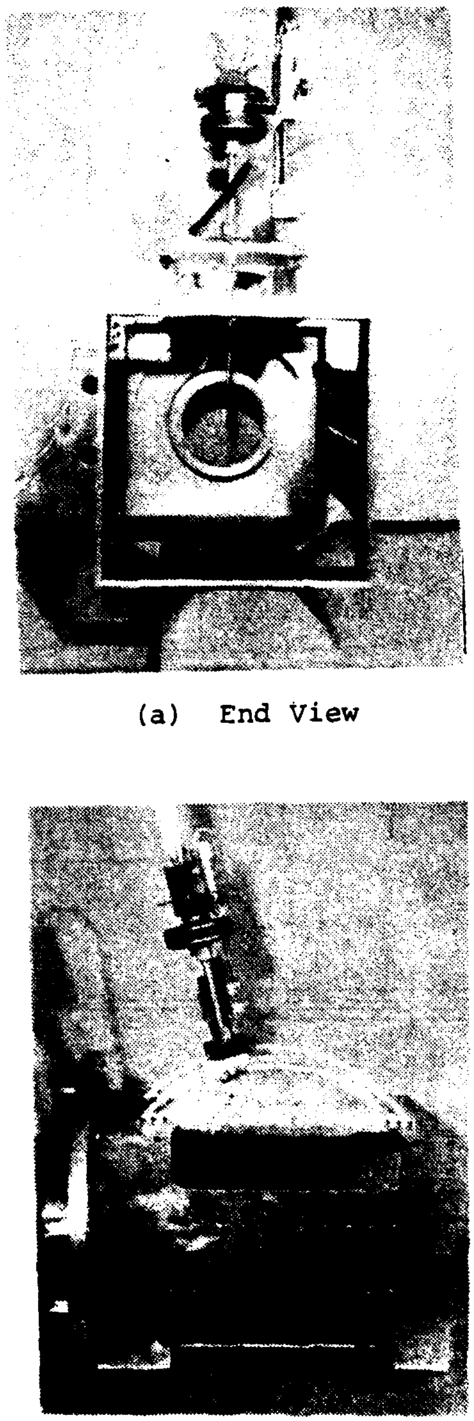



Figure 4. Tip Design Detail and Modifications



(a) End View

(b) Side View

Figure 5. Free-Jet Calibration Apparatus

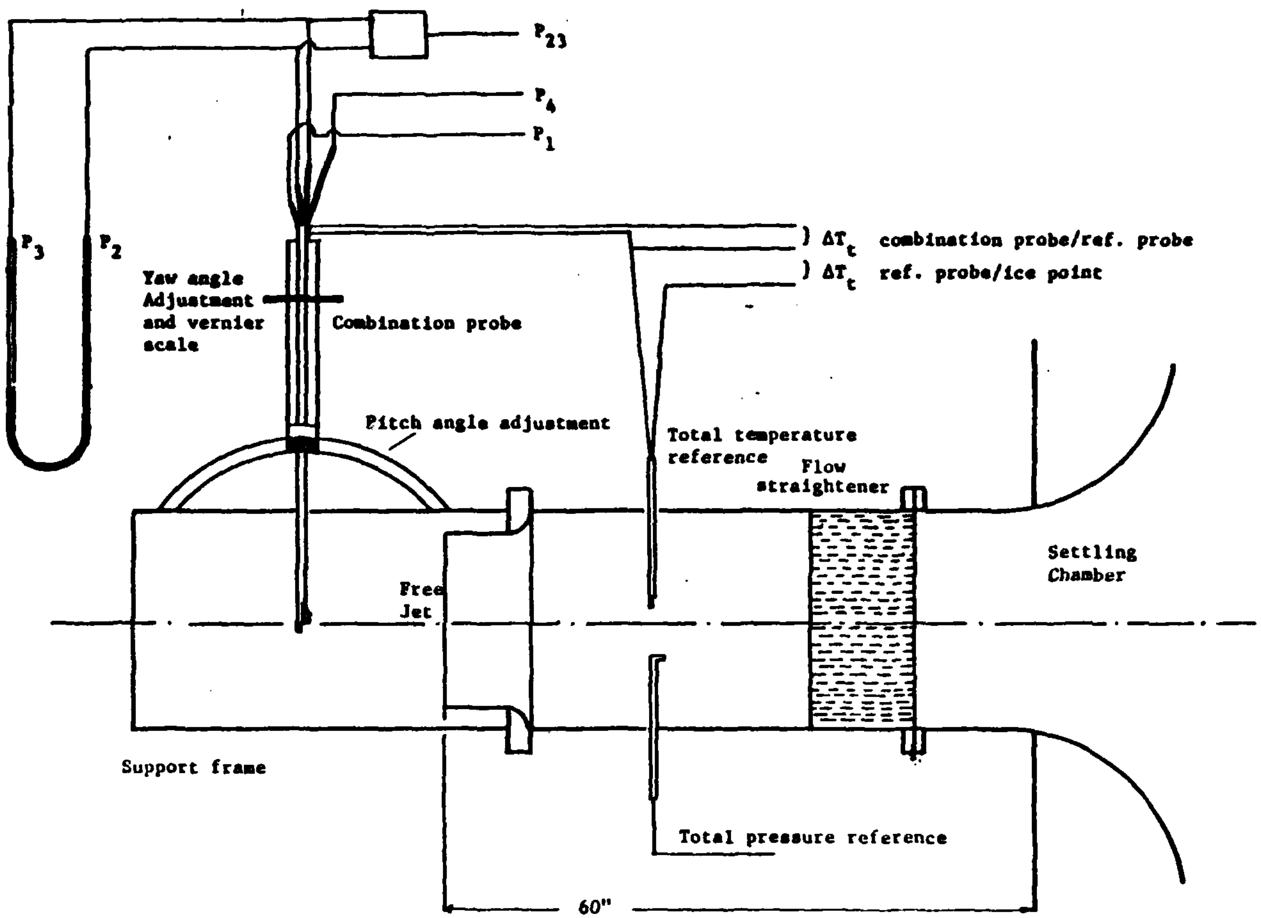



Figure 6. Calibration Facility Geometry (not to scale)

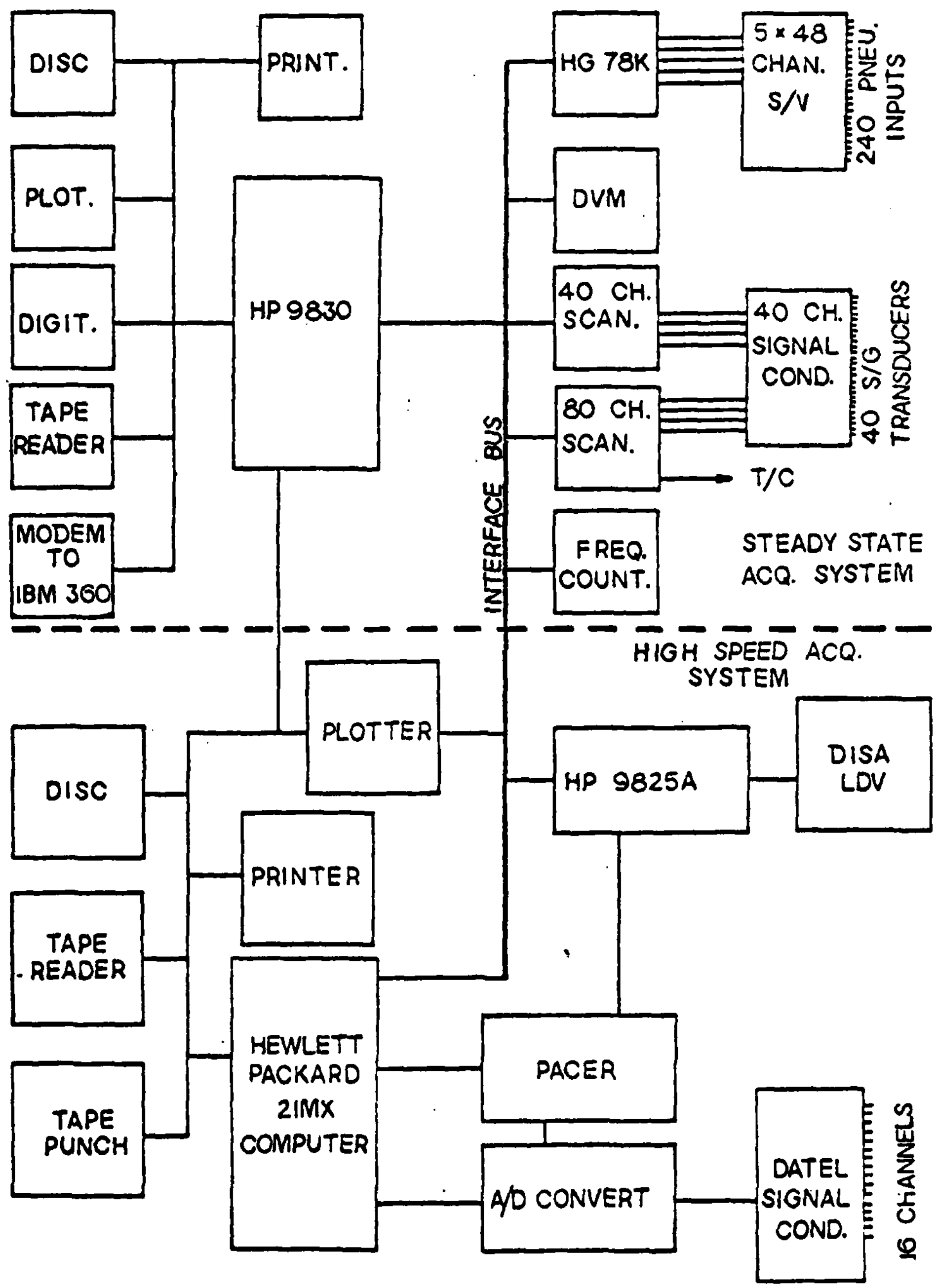



Figure 7. Data Acquisition System

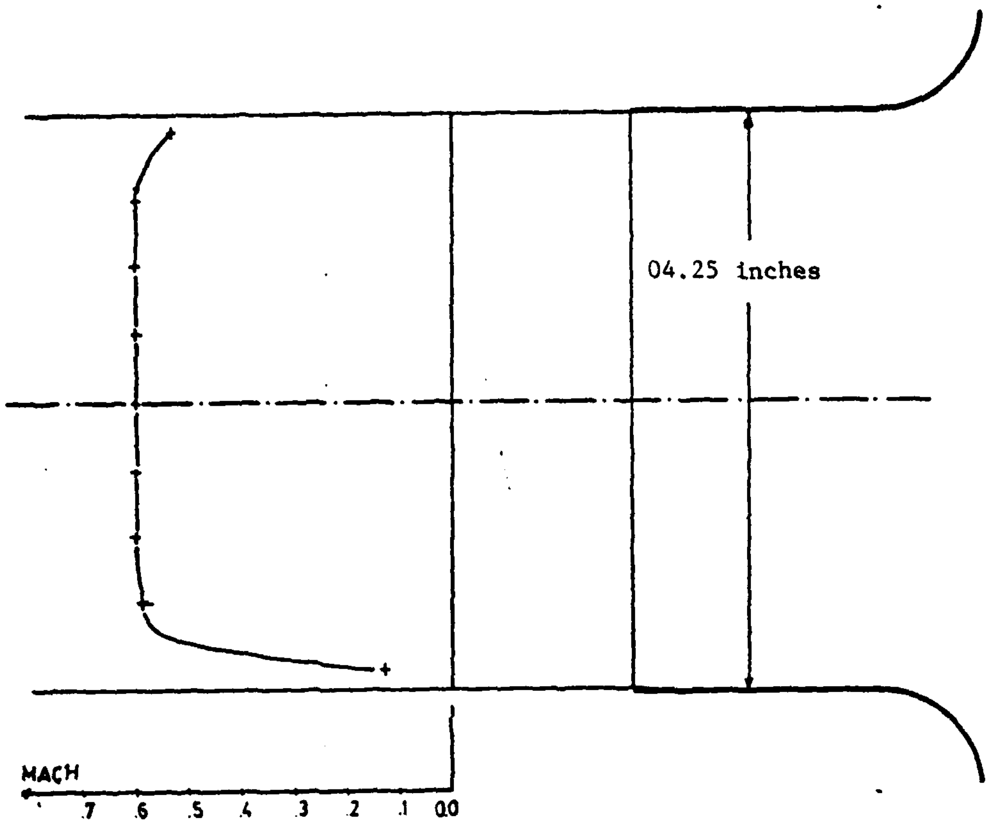



Figure 8. Velocity Distribution Measured Across the Jet

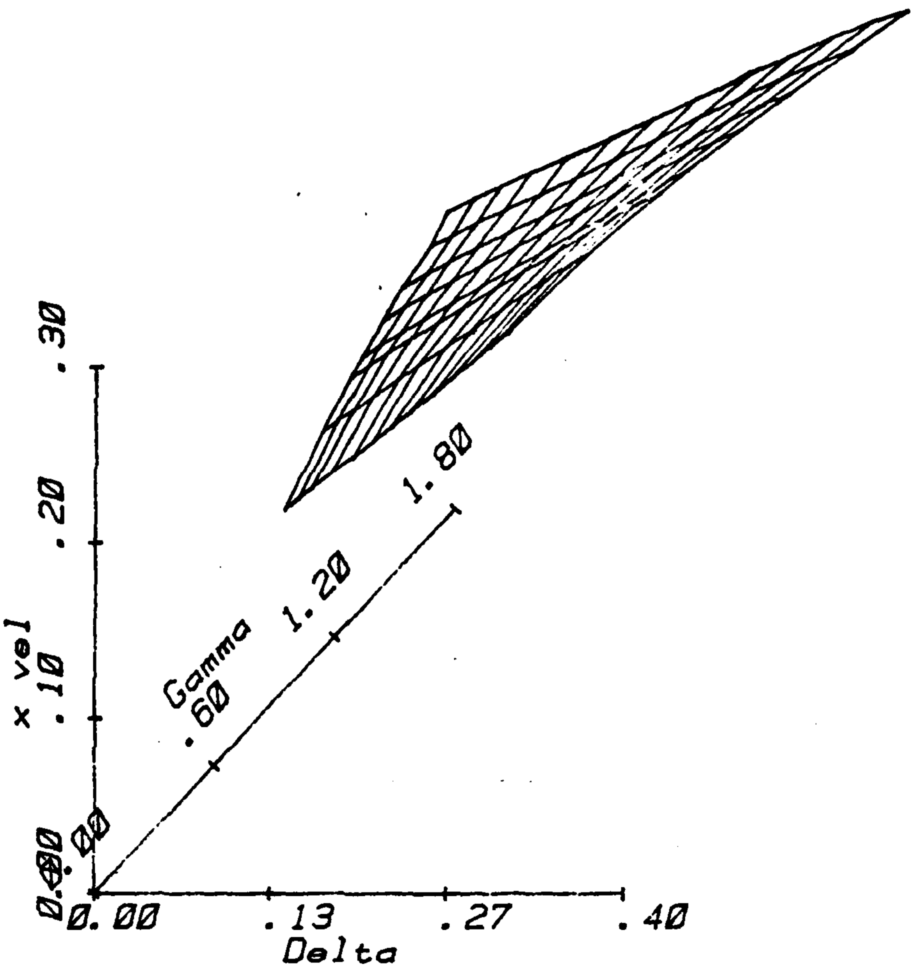



Figure 9. Surface Approximation for Dimensionless Velocity

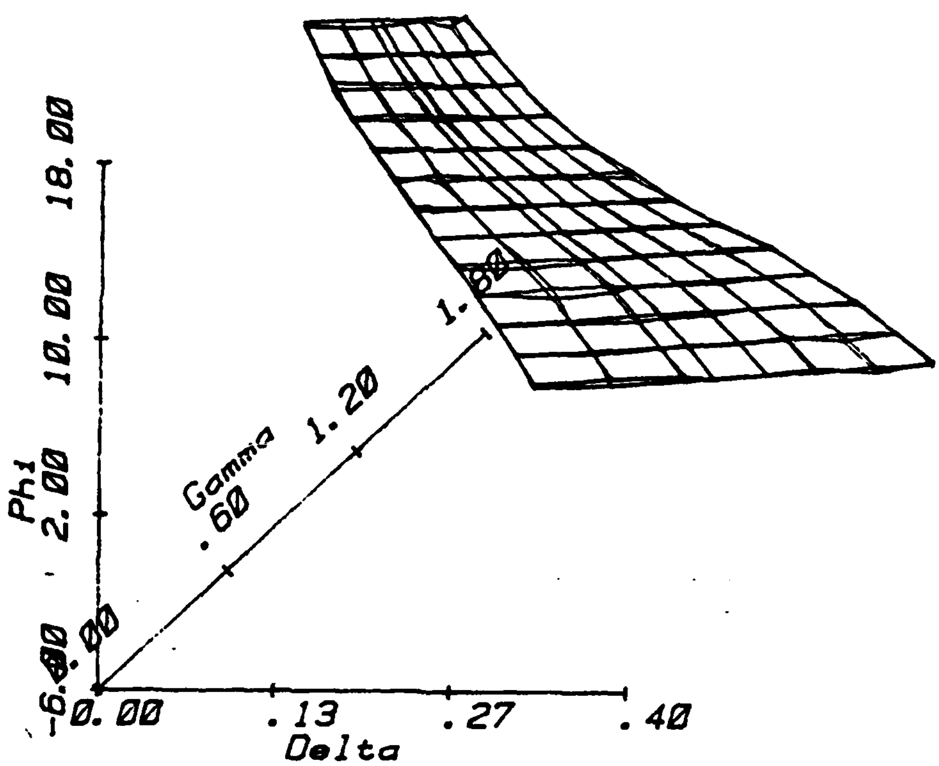



Figure 10. Surface Approximation for Pitch Angle

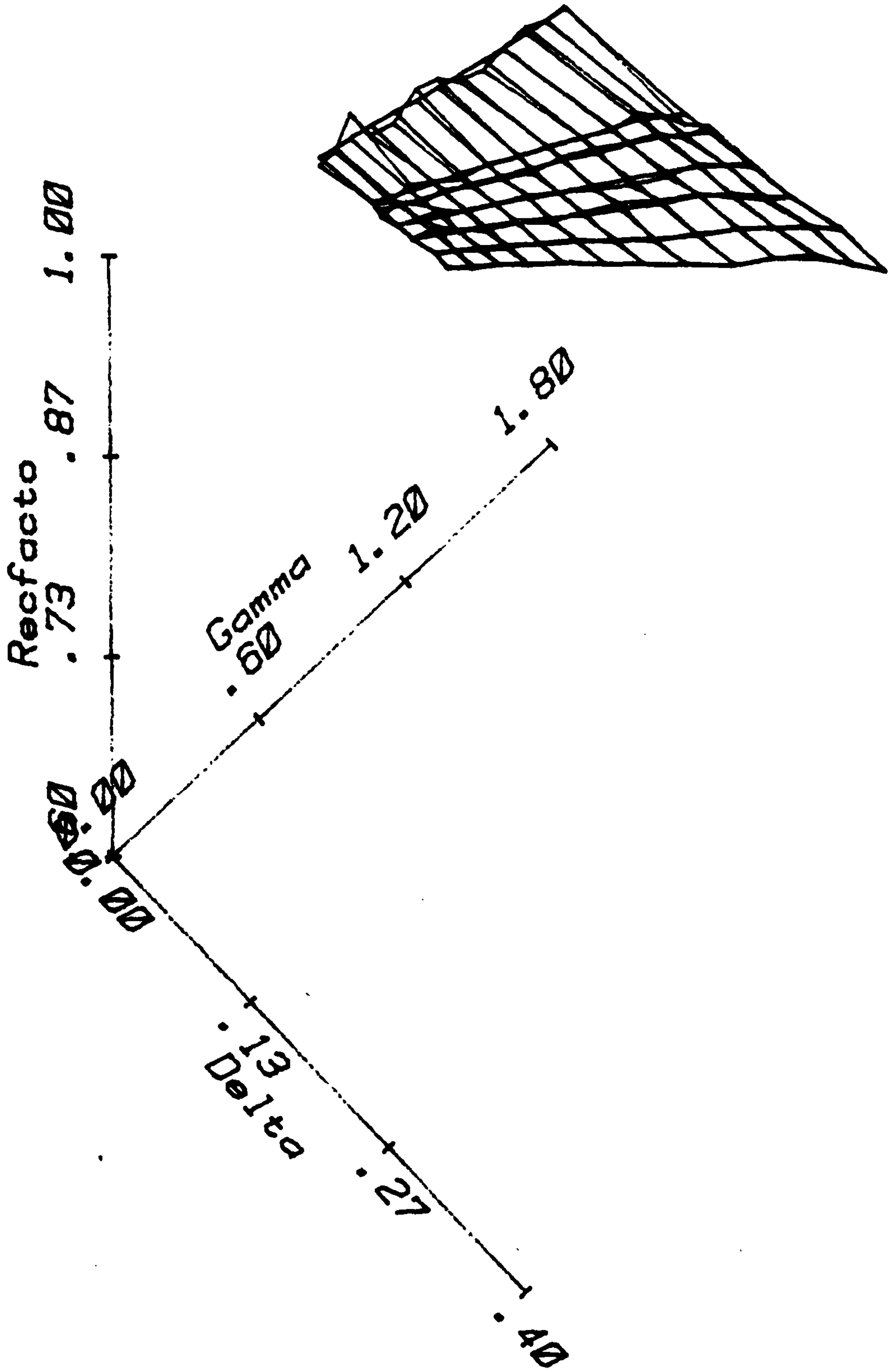



Figure 11. Surface Approximation for Temperature Recovery Factor

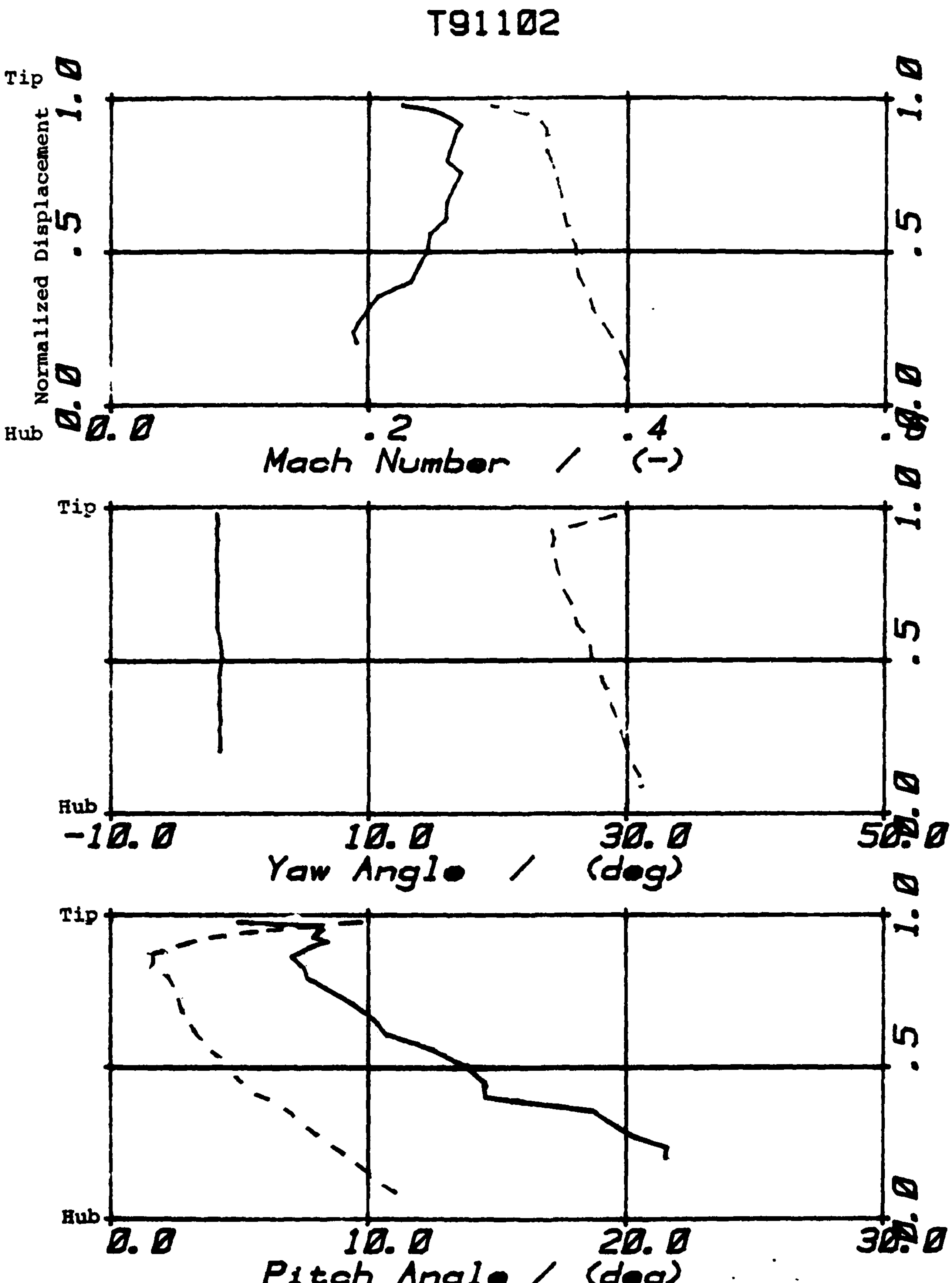



Figure 12. Results of Probe Surveys in the Compressor
——— Inlet, - - - - Outlet of Rotor

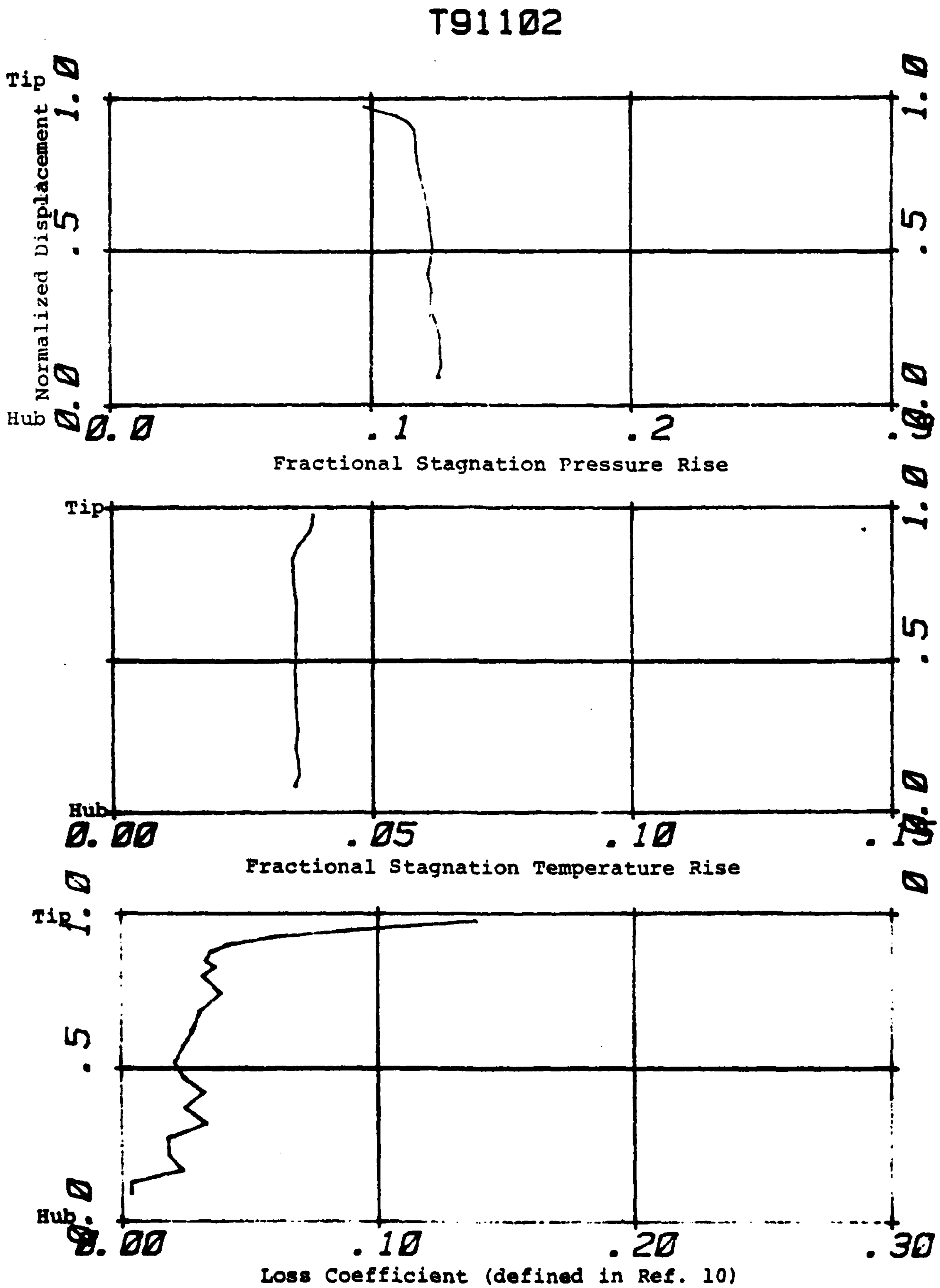



Figure 12 (Cont'd). Results of Probe Surveys in the Compressor

## APPENDIX A. RELATIONSHIP OF PROBE PRESSURE TO FLOW VELOCITY AND ANGLE (by R. P. Shreeve)

### A-1. Dimensionless Velocity and Mach Number

The velocity (V) can be made dimensionless by dividing by the "limiting" or "total" velocity ($V_t$) which, for a perfect gas is given by

$$V_t = \sqrt{2C_pT_t} \qquad A(1)$$

where $T_t$ is the total temperature. $V_t$ is the maximum steady velocity that the flow can have if the stagnation temperature remains unchanged since, by definition

$$C_pT_t = C_pT + \frac{V^2}{2} \qquad A(2)$$

and if the flow is accelerated to the limit of $T \to 0$, the velocity is that given by Equation A(1).

The dimensionless velocity obtained by dividing the velocity by its limiting value can be viewed as the "Fractional Velocity" or simply the "dimensionless velocity" and is here given the symbol X; thus

$$X = \frac{V}{V_t} \qquad A(3)$$

The relationship in Equation A(2) can be seen to give

$$\frac{T}{T_t} = 1 - X^2 \qquad A(4)$$

so that, using isentropic relationships, the ratio of the static (p) to total pressure ($p_t$) is given by

$$\frac{p}{p_t} = \left(\frac{T}{T_t}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 - X^2\right)^{\frac{\gamma}{\gamma-1}} \qquad A(5)$$

and static ($\rho$) to total density ($\rho_t$) is given by

$$\frac{\rho}{\rho_t} = \frac{p}{p_t}^{\frac{1}{\gamma}} = \left(1 - X^2\right)^{\frac{1}{\gamma-1}} \qquad A(6)$$

Using Equation A(2) and the definition of Mach number in a perfect gas, the relationship between the dimensionless velocity and Mach number can be shown to be

$$X^2 = \frac{\frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M^2} \qquad A(7)$$

or

$$\frac{\gamma-1}{2} M^2 = \frac{X^2}{1-X^2} \qquad A(8)$$

Clearly there is a non-linear but one-to-one relationship between X and M, so that if one is known so, uniquely, is the other. In compressor and turbine flows it is often more desirable to work with the dimensionless velocity, X, since it is directly proportional to the velocity itself until the stagnation temperature is changed, as across a rotor. The relationships in Equations A(4), A(5) and A(6) are also simpler than the corresponding expressions involving Mach number.

In representing the calibration of the probe, the dimensionless velocity, rather than Mach number, was used.

A-2. Probe Pressure Coefficients

The probe geometry is constant and when used is always adjusted so that the probe is aligned (in yaw) with the flow. Therefore, by dimensional analysis, the pressure coefficient, $C_{p_n}$, defined as

$$C_{p_n} = \frac{p_n - p}{\frac{\gamma}{2} p M^2} \qquad A(9)$$

where $p_n$ is the pressure at sensor n, p and M are the static pressure and Mach number respectively of the oncoming flow, and $\gamma$ is the ratio of specific heats, can be only a function of the Mach number, pitch angle ($\phi$) and Reynolds Number ($R_e$), if a perfect gas and uniform flow are assumed.

As a consequence, the difference between the pressure coefficients at two sensors, m and n, defined as

$$C_{p_{mn}} = C_{p_m} - C_{p_n} = \frac{p_m - p_n}{\frac{\gamma}{2} p M^2} \qquad A(10)$$

must also be only a function of $R_e$, M and $\phi$.

The Equation A(10) can be rewritten as

$$C_{p_{mn}} = \left(\frac{p_m - p_n}{p_m}\right) \cdot \left(\frac{p_m}{p_t}\right) \cdot \left(\frac{p_t}{p}\right) \cdot \left(\frac{2}{\gamma M^2}\right) \qquad A(11)$$

where $p_t$ is the stagnation pressure. Using Equation A(5) and Equation A(8), Equation A(11) can be expressed as

$$C_{p_{mn}} = \left(\frac{p_m - p_n}{p_m}\right) \cdot \left(\frac{p_m}{p_t}\right) \cdot \frac{1}{\nu} \qquad A(12)$$

where $\nu$ is an explicit function of the dimensionless velocity (or Mach number); namely,

$$\nu = \left(\frac{\gamma}{\gamma-1}\right) X^2 \left(1 - X^2\right)^{\frac{1}{\gamma-1}} \qquad A(13)$$

Consequently, using Equation A(12), in general

$$\frac{p_m - p_n}{p_m} = \frac{C_{p_{mn}}}{(p_m/p_t)} \cdot \nu \qquad A(14)$$

where the quantities on the left hand side involve only the sensor measurements and where it is known that $C_{p_{mn}}$ depends on $R_e$, M (or X) and $\phi$, and $\nu(X)$ is given explicitly by Equation A(13). From Equation A(9), Equation A(5) and Equation A(7) it must follow also that the ratio $p_m/p_t$ depends only on $R_e$, M and $\phi$

In principle, from an examination of Equation A(14), four independent sensors are necessary in order to calibrate a pressure probe uniquely for variations in M, $R_e$ and $\phi$. The present probe, when rotated to balance $p_2$ and $p_3$ (approximately) has only three independent measurements; namely, $p_1$, $p_{23}$ and $p_4$, where $p_{23}$ is the pneumatic average of the nearly-equal pressures $p_2$ and $p_3$. Only two independent parameters of the type in Equation A(14) can therefore be written. They are defined as

$$\beta = \frac{p_1 - p_{23}}{p_1} \qquad A(15)$$

and

$$\delta = \frac{p_1 - p_4}{p_1} \qquad A(16)$$

where an alternate for either one is obtained in the ratio

$$\gamma = \frac{\delta}{\beta} = \frac{p_1 - p_4}{p_1 - p_{23}} \qquad A(17)$$

However, the geometry of the sensors is such that the effect of Reynolds number on the pressure coefficients should be extremely small in the range of Mach number of interest, and this has been verified experimentally (Reference 6 ). Therefore, in principle, calibration is required to establish the relationships

$$\beta = \beta(X,\phi) \qquad A(18)$$

and

$$\delta = \delta(X,\phi) \qquad A(19)$$

or

$$\gamma = \gamma(X,\phi) . \qquad A(20)$$

The selection of $\beta$, $\delta$ or $\gamma$ is not arbitrary because it involves a selection between different sensitivities. For example, from Equation A(14)

$$\beta = \frac{p_1 - p_{23}}{p_1} = \frac{C_{p_{12}}}{(p_1/p_t)} \cdot \nu(X)$$

Since $C_{p_{12}}$ will probably not be strongly sensitive to Mach number, and $(p_1/p_t)$ will be very close to unity for moderate pitch angles, $\beta$ is a direct measure of the function $\nu(X)$ and therefore of the Mach number, with a second order dependence on pitch angle. In contrast

$$\delta = \frac{p_1 - p_4}{p_1 - p_{23}} = \frac{C_{p_{14}}}{C_{p_{12}}}$$

will not depend much on Mach number but, through $C_{p_{14}}$, because of the orientation of the sensors, will be highly sensitive to pitch angle. The quantity $\gamma$, given by

$$\gamma = \frac{p_1 - p_4}{p_1} = \frac{C_{p_{14}}}{(p_1/p_t)} \cdot \nu$$

will again be directly a measure of Mach number but, because of $C_{p_{14}}$, will also be strongly dependent on pitch angle.

# APPENDIX B. DATA ACQUISITION AND REDUCTION

## B-1. Data Acquisition Using BASIC Program AQCPRB

The data acquisition was carried out using a Hewlett Packard Model 9830A Calculator as controller. BASIC language program AQCPRB was written and stored on mass storage platter PL-001. A program listing is given in Section B-3.1.

The connections of the instrumentation shown in Figure 6 to the data acquisition system shown in Figure 7 are given in Table B-I. The data files containing the raw data stored on PL-001 are given in Table B-II.

## B-2. Data Reduction Using FORTRAN Programs REST2 and COEFS

The data reduction was carried out using a Hewlett Packard Model HP21MX computer (Figure 7). First, the data files given in Table B-II were transferred to the HP21MX using the system utility FORTRAN program X9830 (stored on cartridge 28) on the HP21MX, and BASIC program 9830X on the HP9830A. The data file names were retained on the HP21MX.

Second, Program REST2 (cartridge 28) was used to collect the raw data files, reduce the data to pressure coefficients, temperatures and recovery factors, and then to store the reduced data in a single large data file CALNEW (on cartridge 28). The complete reduced data in CALNEW are shown in Table B-III and the listing of program REST2 is given in Section B-3.2.

The process of obtaining the coefficients of surface approximations to the calibration data was carried out using program COEFS (on cartridge 28) which is listed in Section B-3.3. The program reads the reduced data file CALNEW into an array. The surface approximation procedure is carried out for the dimensionless velocity X, the pitch angle, or the temperature recovery factor as required; one at a time. Whichever is required must be specified in all the statements which carry an asterisk in column #73. (In the listing in Section B.3.3 it is the pitch angle).

To output the plot correctly, the statements with asterisks in columns #73 and #74 must be edited to adjust the range of the Z-axis.

The order of the approximation is input by the operator and can be varied interactively up to an order of 6 for both independent variables. The coefficients for the approximations and the errors for each data point (see Equations 4, 5 and 10) are printed and plotted and the operator is asked for a name for the file in which to store the coefficients.

## B-3. Program Listings

The following pages contain:

B-3.1 Basic Program ACQPRB

B-3.2 Fortran Program REST2

B-3.3 Fortran Program COEFS.

## B-3.1. Basic Program AQCPRB

```
10 REM******AQCPRB*************************************
20 REM******ON-LINE DATA ACQUISITION PROGRAM***********
30 REM******FOR A COMBINATION  PROBE*****************
40 REM
50 REM-- NOTE : THIS PROGRAM ONLY ACQUIRES THE RAW DATA,
60 REM--        MULTIPLIES IT WITH THE APPROPRIATE SCALING
70 REM--        FACTOR AND STORES IT.
80 REM
90 REM
100 REM
110 REM
120 REM
130 DIM A[14,12],B[3],A$[6],C$[20],R$[3],H$[3]
140 MAT A=ZER
150 DISP "ENTER NO. OF PITCH ANGLE(MAX.13)";
160 INPUT P9
170 FOR J=1 TO P9
180 DISP "ENTER PITCH ANGLE ("J")";
190 INPUT A[J,12]
200 REM
210 REM     DESCRIPTION:
220 REM       THIS SECTION PERFORMS SEQUENTIAL SCANNING
230 REM     OF SCANIVALVE 'V' BETWEEN PORT ADDRESSES SPECIFIED.
240 REM
250 REM     VARIABLES:
260 REM       V  = DESIRED S/V
270 REM       A1 = LOW PORT
280 REM       A2 = HIGH PORT
290 REM       P  = PRESENT S/V PORT
300 REM       S  = STEP SIZE
310 REM
320 REM     AUTHOR: R.N. GEOFFARTH,LT USN
330 REM     DATE:   FEB 79
340 REM
350 FORMAT B
360 FORMAT 2B
370 FORMAT 3B
380 FORMAT 4B
390 FORMAT F3.0
400 WRITE (13,380)256,20,768,512;
```

```
410 CMD "?D#","F1R7M3A0H0T3"
420 V=2
430 S=1
440 IF V#2 THEN 460
450 S=2
460 CMD "?D'"
470 WRITE (13,350)V;
480 WRITE (15,490)V
490 FORMAT "SCANIVALVE #",F3.0,/,/," PORT",8X,"VOLTAGE(UNCORR.)"
500 FOR A=2 TO 12 STEP S
510 GOSUB 1690
520 CMD "?D!"
530 WRITE (13,390)V+9
540 CMD "?D#","T3"
550 CMD "?C$"
560 ENTER (13,*)V0
570 WRITE (15,580)P,V0
580 FORMAT 1X,F3.0,4X,F12.6
590 K=A/S
600 REM  WRITE (15,610)K
610 REM   FORMAT 10X,"THIS IS K :",F6.2,/
620 A[J,K]=V0
630 CMD "?D!","C"
640 NEXT A
650 OUTPUT (13,380)256,20,768,512;
660 CMD "?D#","F1R7M3A1H1T3"
670 R=1
680 R$="?D!"
690 WRITE (15,700)R
700 FORMAT 5X,"SCANNER #",F2.0,/,2X,"CHAN",6X,"DATA"
710 B=25
720 S1=0
730 FOR L=1 TO 10
740 CMD R$
750 OUTPUT (13,390)B
760 CMD "?D#"
770 OUTPUT (13,370)256,8,512;
780 CMD "?C$"
790 ENTER (13,*)D1
800 S1=S1+D1
```

```
810 NEXT L
820 V=S1/10
830 WRITE (15,840)B,V
840 FORMAT 2X,F3.0,3X,F10.6
850 K=K+1
860 REM  WRITE (15,610)K
870 FORMAT 5X,/,/,F5.2
880 A[J,K]=V
890 CMD "?D(!","C"
900 H=2
910 H$="?D("
920 WRITE (15,700)H
930 FOR B=20 TO 23
940 S1=0
950 FOR L=1 TO 10
960 CMD H$
970 OUTPUT (13,390)B
980 CMD "?D#"
990 OUTPUT (13,370)256,8,512;
1000 CMD "?C$"
1010 ENTER (13,*)D1
1020 S1=S1+D1
1030 NEXT L
1040 V=S1/10
1050 WRITE (15,840)B,V
1060 K=K+1
1070 REM WRITE (15,610)K
1080 A[J,K]=V
1090 NEXT B
1091 CMD "?D(!","C"
1100 NEXT J
1110 GOTO 1120
1120 REM****DATA STORAGE*****
1130 PRINT
1140 PRINT
1150 DIM T$[15],U$[15],V$[15],W$[15],X$[15],Z$[15],O$[16],P$[16],Q$[16],Y$[16]
1160 DIM S$[16],N$[18]
1170 N$="  P BARO (INCH HG)"
1180 P$="     T PIPE(IP) "
1190 Q$="       T TUNNEL"
1195 Y$="      T JET(IP)"
1200 S$="D T(PIPE-COMB)"
```

```
1210 T$="    PA-PA "
1220 U$="   PCAL-PA**"
1230 V$="     P1-PA "
1240 W$="   P23-PA "
1250 X$="    P4-PA "
1260 Z$="   PK-PA "
1270 O$="          ** PHI "
1280 WRITE (15,1290)
1290 FORMAT 2X,"RAW DATA WITH VOLTAGE CORRECTED TO PRESSURES(IN.H2O)",/
1300 WRITE (15,1310)T$,U$,V$,W$,X$,Z$,N$
1310 FORMAT F10.0,F12.0,4F10.0,F18.0
1320 FOR J=1 TO P9
1330 A[J,1]=A[J,1]*100000
1340 A[J,2]=A[J,2]*100000
1350 A[J,3]=A[J,3]*100000
1360 A[J,4]=A[J,4]*100000
1370 A[J,5]=A[J,5]*100000
1380 A[J,6]=A[J,6]*100000
1390 A[J,7]=A[J,7]*10000
1400 WRITE (15,1410)A[J,1],A[J,2],A[J,3],A[J,4],A[J,5],A[J,6],A[J,7]
1410 FORMAT F10.4,F9.3," **",3F10.4,F9.3,F12.3
1420 NEXT J
1430 PRINT
1440 PRINT
1450 PRINT
1460 WRITE (15,1470)
1470 FORMAT 3X,"RAW DATA CORRECTED TO READINGS IN MILLIVOLTS",/
1480 WRITE (15,1490)Q$,P$,S$,Y$,O$
1490 FORMAT 5F16.0
1500 FOR J=1 TO P9
1510 A[J,8]=A[J,8]*1000
1520 A[J,9]=A[J,9]*1000
1530 A[J,10]=A[J,10]*1000
1540 A[J,11]=A[J,11]*1000
1545 A[J,12]=A[J,12]
1550 WRITE (15,1560)A[J,8],A[J,9],A[J,10],A[J,11],A[J,12]
1560 FORMAT 5F15.4
1570 NEXT J
1580 DISP "INPUT DATA FILE NAME D-----";
1590 INPUT A$
1600 FILES *
```

```
1610 ASSIGN A$,1,K
1620 MAT PRINT # 1;A
1630 IF END#1 THEN 1660
1640 PRINT "DATA STORED IN",A$
1650 END
1660 DISP "END MARKER READ";
1670 STOP
1680 REM*****************************************
1690 REM  SUBROUTINE "POSIT"
1700 GOSUB 1880
1710 D=A-P
1720 CMD "?D!"
1730 IF D<0 THEN 1760
1740 IF D>0 THEN 1810
1750 RETURN
1760 REM    HOME S/V
1770 WRITE (13,390)V+4
1780 WRITE (13,*)"C"
1790 WAIT 4000
1800 GOTO 1700
1810 REM     ADVANCE S/V
1820 FOR I=1 TO D STEP S
1830 WRITE (13,390)V-1
1840 WRITE (13,*)"C"
1850 WAIT 50
1860 NEXT I
1870 GOTO 1700
1880 REM     READ S/V ADDRESS
1890 CMD "?G$"
1900 P0=RBYTE13
1910 L=BIAND(P0,15)
1920 T=ROT(P0,4)
1930 M=BIAND(T,7)
1940 P=10*M+L
1950 WRITE (13,360)256,95;
1960 RETURN
```

## B-3.2. Fortran Program REST2

```
&REST2 T=00004 IS ON CR00028 USING 00030 BLKS R=0000
FTN4,L
      PROGRAM REST (3,99)
     *, Restore calibration data to new structure.
C     ******************************************************************
C     *                                                                *
C     * RESTORES RAW CALIBRATION DATA FROM COMBINATION PROBE TO NEW    *
C     * STRUCTURE.                                                     *
C     *                                                                *
C     ******************************************************************
      INTEGER IDCB(144),IFILE(3),ISIZE(2)
      INTEGER NOLF,NOCR(2),ICLR(3)
      REAL A(14,12)
      REAL GAMMA(16,16),DELTA(16,16),XVEL(16,16),PHI(16,16),RECF(16,16)
      DATA IDCBS  /144/
      DATA NOLF  /006537B/
      DATA NOCR  /000033B,040433B/
      DATA ICLR  /015524B,015515B,006537B/
  108 FORMAT (" ENTER FILE (XCPRB RAW DATA!"/
     *" DON'T FORGET SECURITY CODE & CARTRIDGE REFERENCE NUMBER!"/
     *"DCPRB  :   :   "A2)
  109 FORMAT ("  I   / J  "12I6,A2)
  110 FORMAT ("  "I3,4X,F6.4,F6.3,4F6.4,F6.1,4F6.4,I6,A2)
  111 FORMAT (" OUTPUT INPUT DATA TO ANY OTHER DEVICE?  ENTER NO
     * OR LU# !"/"  "A2)
  112 FORMAT ("  I   / J  "12I10)
  113 FORMAT("  "I3,5X,F9.7,1X,F9.6,1X,4(F9.7,1X),F9.1,1X,4(F9.6,1X),I9)
  119 FORMAT (//1X"       Beta       Gamma       Delta       X vel
$     Machno.      Phi    T Tunnel  T ref pipe  Tcombprobe
$Rec.Fac")
  120 FORMAT (2X,10(F10.6,2X))
  121 FORMAT (//" REARRANGED DATA ARRAYS"/)
  122 FORMAT(" GAMMA("I2","I2")="F10.6"  DELTA("I2","I2")="F10.6" X VEL(
     *"I2","I2")="F10.6"  PHI("I2","I2")="F10.3" RECF("I2","I2")="F10.6)
  123 FORMAT (" MORE DATA YES OR NO "2A2)
  149 FORMAT ((3A2))
  151 FORMAT (3A2,1X,I2,1X,I2)
  161 FORMAT (I2)
  162 FORMAT (//" THE DATA FROM DATA SET #"I2" OF FILE "3A2" ARE
     *"/)
 1111 FORMAT ("Statement # "I6" Error # "I5" Encountered!")
      LI = LOGLU(ISESSN)
   77 WRITE (LI, 111) NOLF
      READ  (LI, 149) IDUM
      WRITE (LI, 149) (ICLR,I1=1,2)
      IF ( IDUM  .EQ.  2HNO ) GO TO 78
      CALL CODE
      READ  (IDUM,161) LO
      IF ( LO  .EQ.   1 ) GO TO 79
      IF ( LO  .EQ.   6 ) GO TO 79
      IF ( LO  .EQ.  18 ) GO TO 79
```

```
      GO TO 77
   78 LO = 0
   79 IF ( LO   .EQ.  LI ) LO = 0
      NMACH = 0
C     .................................................................
C     .                                                               .
C     .  PRESET NEW DATA ARRAYS.                                      .
C     .                                                               .
C     .................................................................
      DO 81  I=1,16,1
      DO 81  J=1,16,1
      GAMMA(I,J) = 0.
      DELTA(I,J) = 0.
      X VEL(I,J) = 0.
      PHI(I,J)   = 0.
   81 RECF(I,J)  = 0.
   80 NMACH = NMACH+1



C     .................................................................
C     .                                                               .
C     .  READ FILE DCPRB  FROM DISC INTO ARRAY A.                     .
C     .                                                               .
C     .................................................................
      WRITE (LI, 108) NOLF
      READ  (LI, 151) IFILE,ISECU,ICR
      IF ( ICR  .EQ.  0 ) ICR = 28
      IL = 336
      K1=1
      CALL OPEN  (IDCB,IERR,IFILE,IOPTN,ISECU,ICR,IDCBS)
      JJ = 11
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL RWNDF (IDCB,IERR)
      JJ = 12
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL READF (IDCB,IERR,A,IL)
      JJ = 13
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL CLOSE (IDCB,IERR,0)
      JJ = 14
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
```

```
C       ..........................................................
C       .                                                        .
C       .  OUTPUT INPUT DATA.                                    .
C       .                                                        .
C       ..........................................................
        WRITE (LI, 162) K1,IFILE
        IF ( LO  .NE.  0 ) WRITE (LO, 162) K1,IFILE
        WRITE (LI, 109) (J2,J2=1,12,1),NOLF
        IF ( LO  .NE.  0 ) WRITE (LO, 112) (J2,J2=1,12,1)
        DO 05 I1=1,14,1
        IF ( LO  .NE.  0 ) WRITE (LO, 113) I1,(A(I1,J2),J2=1,12,1)
     05 WRITE (LI, 110) I1,(A(I1,J2),J2=1,12,1),NOLF
        WRITE (LI, 119)
        IF ( LO  .NE.  0 ) WRITE (LO, 119)


C       ..........................................................
C       .                                                        .
C       .  DEFINE DELTA AND WRITE   ,  , X vel AND   INTO NEW ARRAY.  .
C       .                                                        .
C       ..........................................................
        NPITCH = 13
        DO 4712 J1=1,NPITCH,1
        B0 = (A(J1,3)-A(J1,4))/(A(J1,3)+30.0300*13.585-A(J1,1))
        G0 = (A(J1,3)-A(J1,5))/(A(J1,3)-A(J1,4))
        D0 = B0*G0
        X0=SQRT(1-(30.0300*13.585/(A(J1,6)+30.0300*13.585-A(J1,1)))**
       *(0.471.4))
        XM0 = SQRT((5*X0*X0)/(1-(X0*X0)))
        P0 = A(J1,12)
        TTUN = 32.6149+34.7279*A(J1,8)
        TREFP= 31.6149+30.6827*A(J1,9)-.3079*A(J1,9)*A(J1,9)
C       TREFJ= 31.6149+30.6827*A(J1,11)-.3079*A(J1,11)*A(J1,11)
        TCOMB= 31.6149+30.6827*(A(J1,9)+A(J1,10))-.3079*(A(J1,9)+
       *        A(J1,10))*(A(J1,9)+A(J1,10))
        R0   = 1 - ((TREFP-TCOMB)/(X0*X0*(TREFP+460)))
        WRITE(LI,120) B0,G0,D0,X0,XM0,P0,TTUN,TREFP,TCOMB,R0
        IF (LO .NE. 0)  WRITE(LO,120) B0,G0,D0,X0,XM0,P0,TTUN,TREFP,TCOMB,
       *R0
        GAMMA(NMACH,J1) = G0
        DELTA(NMACH,J1) = D0
        X VEL(NMACH,J1) = X0
        PHI(NMACH,J1)   = P0
        RECF(NMACH,J1)  = R0
   4712 CONTINUE

```

```
C
C     ..........................................................................
C     .                                                                        .
C     .  OUTPUT NEW DATA ARRAY.                                                .
C     .                                                                        .
C     ..........................................................................
      WRITE (LI, 121)
      I = NMACH
      DO 10 J=1,16,1
      IF ( LO  .NE.  0 ) WRITE (LO, 122) I,J,GAMMA(I,J),I,J,DELTA(I,J),I,
     *,J,XVEL(I,J),I,J,PHI(I,J),I,J,RECF(I,J)
   10 CONTINUE



C     ..........................................................................
C     .                                                                        .
C     .  DECISION, WHETHER TO REARRANGE MORE FILES.                            .
C     .                                                                        .
C     ..........................................................................
      WRITE (LI, 123) NOCR
      READ  (LI, 149) IDUM
      IF ( IDUM  .EQ.  2HYE ) GO TO 80



C     ..........................................................................
C     .                                                                        .
C     .  STORE NEW DATA ARRAY IN FILE CALNEW.                                  .
C     .                                                                        .
C     ..........................................................................
      IFILE(1)  =  2HCA
      IFILE(2)  =  2HLN
      IFILE(3)  =  2HEW
      ISIZE(1)  =    20
      ISIZE(1)  =   128
      ITYPE     =     1
      CALL CREAT (IDCB,IERR,IFILE,ISIZE,ITYPE,0,28,IDCBS)
      JJ = 15
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL OPEN  (IDCB,IERR,IFILE,IOPTN,0,28,IDCBS)
      JJ = 16
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,GAMMA,512,1)
      JJ = 17
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,DELTA,512,5)
      JJ = 18
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,XVEL,512,9)
```

```
      JJ = 21
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,PHI,512,13)
      JJ = 22
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,RECF,512,17)
      JJ = 23
      IF ( IERR  .LT.  0 ) WRITE(1,1111) JJ,IERR
      CALL CLOSE (IDCB,IERR,0)
      JJ = 24
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR

      WRITE (6,2345) IFILE
      DO 99  I=1,8,1
      WRITE(6,4567) I
   99 WRITE(6,3456) (GAMMA(I,J),DELTA(I,J),XVEL(I,J),PHI(I,J),RECF(I,J)
     *,J=1,13,1)
 2345 FORMAT("  THESE ARE DATA FROM FILE :"3A2//"    GAMMA    DELTA
     *XVEL        PHI      RECF")
 3456 FORMAT(5(1X,F8.9))
 4567 FORMAT("  MACH NUMBER = "I3/)


      STOP 7777
      END
```

## B-3.3. Fortran Program COEFS

```
&COEFS T=00004 IS ON CR00028 USING 00039 BLKS R=0000

FTN4,L
      PROGRAM COEFS (3,99)
C     .................................................................
C     .                                                               .
C     .  This is program COEFS.                                       .
C     .  It approximates the reduced data from the calibration of     .
C     .  a combination probe with a calibration surface which is      .
C     .  expressed mathematically by high order polynominals for      .
C     .  both independed varibles.                                    .
C     .  The reduced data is read from file CALNEW and the coeffi-    .
C     .  cients resulting in the approximation are stored in a        .
C     .  file the operator assigns a name to.                         .
C     .                                                               .
C     .................................................................
     *, CALCULATE CALIBRATION COEFFICIENTS.
      COMMON / AFLD / PLOTR
      COMMON / MATRX / A,B
      COMMON / SUMME / GAMMA,DELTA,PHI                                   *
      REAL PLOTR(256),A(49,49),B(49),COEFF(7,7)
      INTEGER IDCB(144),IFILE(3),ISIZE(2),NOCR(2),ICLR(3)
      REAL GAMMA(16,16),DELTA(16,16),XVEL(16,16),PHI(16,16),RECF(16,16)
      REAL R(16)
      DATA PI /3.141593/
      DATA IFILE /2HCA,2HLN,2HEW/
      DATA NOCR /000033B,040433B/
      DATA ICLR /015524B,015515B,006537B/
      DATA ISECU /0/
      DATA ICR   /28/
      DATA ITYPE /1/
      DATA ISIZE /1,128/

      DATA IDCBS /144/
  101 FORMAT (" ENTER ORDER M OF X - APPROXIMATION "2A2)
  102 FORMAT (" ENTER ORDER N OF Y - APPROXIMATION "2A2)
  103 FORMAT (" CHANGE # OF COEFF'S     ....    1"/
     *        " CHANGE ANGLE FOR AXES ....    2  "2A2)
  104 FORMAT (" ENTER ALPHAX, ALPHAY, XO AND YO")
  105 FORMAT (" ENTER FILE NAME FOR COEFFICIENT FILE: "3A2)
  106 FORMAT (3A2)
  149 FORMAT(""((3A2)))
  601 FORMAT (///" COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FI
     *LE :"3A2/)
  602 FORMAT ((3X,16(6X,I2)))
  603 FORMAT (1X,I2,16(1X,F7.3)/3(3X,16(1X,F7.3)/))
  604 FORMAT (///"ERRORS(%)  AT EACH POINT"/)
  605 FORMAT ((3X,10(11X,I2)))
  606 FORMAT (1X,I2,7(2X,F11.6))
      LT = LOGLU(I)
```

```
C
C      .......................................................................
C      .  INITIALIZE PLOTTER AND DEFINE USER & PLOTTER AREAS.               .
C      .                                                                     .
C      .......................................................................
       CALL INITG (13)
       XPMIN   = 0.
       XPMAX   = 10.
       YPMIN   = 0.
       YPMAX   = 10.
       ZPMIN   = 0.
       ZPMAX   = 10.



C      .......................................................................
C      .                                                                     .
C      .  X - AXIS :  DELTA                                                  .
C      .  Y - AXIS :  GAMMA                                                  .
C      .  Z - AXIS :  PHI OR XVEL OR RECF                                    .
C      .                                                                     .
C      .......................................................................
       XUMIN   = 0.000
       XUMAX   = 0.400
       YUMIN   = 0.000
       YUMAX   = 1.800
       ZUMIN   =        -6.0
       ZUMAX   =        18.0
       ALPHAX  =      7.
       XA      = (XPMAX        -XPMIN        )/(XUMAX-XUMIN)
       XB      = (XPMIN*XUMAX-XPMAX*XUMIN)/(XUMAX-XUMIN)
C
       XL      = (XPMAX        -XPMIN        )
       ALPHAY  =   43.
       YA      = (YPMAX        -YPMIN        )/(YUMAX-YUMIN)
       YB      = (YPMIN*YUMAX-YPMAX*YUMIN)/(YUMAX-YUMIN)
       YL      = (YPMAX        -YPMIN        )
       ALPHAZ  =   90.0
       ZA      = (ZPMAX        -ZPMIN        )/(ZUMAX-ZUMIN)
       ZB      = (ZPMIN*ZUMAX-ZPMAX*ZUMIN)/(ZUMAX-ZUMIN)
       ZL      = (ZPMAX        -ZPMIN        )
       XO      =   5.
       YO      =   5.
    85 PLOTR(61)  = (ALPHAX*PI)/180.
       PLOTR(62)  = (ALPHAY*PI)/180.
       PLOTR(63)  = (ALPHAZ*PI)/180.
       PLOTR(64)  = XO
       PLOTR(65)  = YO
       PLOTR(66)  = XA
       PLOTR(67)  = XB
       PLOTR(68)  = YA
       PLOTR(69)  = YB
       PLOTR(70)  = ZA
       PLOTR(71)  = ZB
```

```
      CALL SETSM (113,1.)
      CALL AXIS (XO,YO,XL,ALPHAX,8H Delta   , 8,XUMIN,XUMAX,4HF6.2,6,3)
      CALL AXIS (XO,YO,YL,ALPHAY,8H Gamma   ,-8,YUMIN,YUMAX,4HF6.2,6,3)
      CALL AXIS (XO,YO,ZL,ALPHAZ,9H Pitch    ,-8,ZUMIN,ZUMAX,4HF6.2,6,3) **


C     .......................................................................
C     .                                                                     .
C     .  READ DATA FILE CALNEW.                                             .
C     .                                                                     .
C     .......................................................................
      JJ = 1
      CALL OPEN (IDCB,IERR,IFILE,IOPTN,0,28,144)
      IF ( IERR  .LT.  0 ) WRITE(1,1001)JJ,IERR
      JJ = 2
      CALL READF (IDCB,IERR,GAMMA,512,LEN,1)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 3
      CALL READF (IDCB,IERR,DELTA,512,LEN,5)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 4
      CALL READF (IDCB,IERR,XVEL,512,LEN,9)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ =5
      CALL READF (IDCB,IERR,PHI,512,LEN,13)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 6
      CALL READF (IDCB,IERR,RECF,512,LEN,17)
      IF ( IERR .LT. 0 ) WRITE(1,1001) JJ,IERR
      CALL CLOSE (IDCB,IERR,0)

C     DO 4321 I = 2,7,1                               NOTE: These statements can be
C     DO 4321 J = 1,13,1                                    used to exclude one or
C     GAMMA(I,J) = GAMMA(I+1,J)                             more machnumbers!
C     DELTA(I,J) = DELTA(I+1,J)
C4321 RECF (I,J) = RECF (I+1,J)

 1001 FORMAT ("  STATEMENT# "I5" ERROR # "F12.7" DETECTED")


C     .......................................................................
C     .                                                                     .
C     .  PLOT CALIBRATION POINTS.                                           .
C     .                                                                     .
C     .......................................................................
      NMACH = 8
      NPITCH = 13
      CALL SETSM (113,2.)
      DO 01 I=1,NMACH,1
      DO 01 J=1,NPITCH,1
      CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))          **
      IF ( J  .EQ.  1 ) CALL PLOT (XPLOT,YPLOT,2)
      IF ( J  .GT.  1 ) CALL PLOT (XPLOT,YPLOT,3)
```

```
C           WRITE(6,1234)DELTA(I,J),GAMMA(I,J),XVEL(I,J),RECF(I,J)
C1234 FORMAT(" DELTA="F9.6" GAMMA="F9.6" XVEL="F6.2" RECF="F9.6)
   01 CONTINUE
      DO 02 J=1,NPITCH,1
      DO 02 I=1,NMACH,1
      CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))
      IF ( I  .EQ.  1 ) CALL PLOT (XPLOT,YPLOT,2)
      IF ( I  .GT.  1 ) CALL PLOT (XPLOT,YPLOT,3)
   02 CONTINUE



C     ...................................................................
C     .
C     .  CALCULATE CALIBRATION SURFACE COEFFICIENTS.                      .
C     .                                                                   .
C     ...................................................................
      CALL SETSM (113,0.)
   91 WRITE (LI,101) NOCR
      READ  (LI,  *) MORDER
      IF (MORDER.GT.6) GO TO 87
   92 WRITE (LI,102) NOCR
      READ  (LI,  *) NORDER
      IF (NORDER.GT.6) GO TO 92
      M=MORDER+1
      N=NORDER+1
      CALL COMAT (A,B,M,N,NMACH,NPITCH)
      NEQUS=M*N
      CALL ELGJ (NEQUS)





      I1=0
      DO 93 I=1,M,1
      DO 93 J=1,N,1
      I1=I1+1
   93 COEFF(I,J)=B(I1)
      WRITE (LI,105)
      READ (LI,106) IFILE
      WRITE(LI,149) ICLR
      CALL CREAT (IDCB,IERR,IFILE,ISIZE,ITYPE,ISECU,ICR,IDCBS)
C     IF ( IERR  .GT.  0 ) STOP 0011
      CALL OPEN  (IDCB,IERR,IFILE,IOPTN,ISECU,ICR,IDCBS)
      IF ( IERR  .LT.  0 ) STOP 0012
      CALL WRITF (IDCB,IERR,COEFF,98)
      IF ( IERR  .LT.  0 ) STOP 0013
      CALL CLOSE (IDCB,IERR,0)
      IF ( IERR  .LT.  0 ) STOP 0014
      WRITE (6,601) IFILE
      WRITE (6,605) (J,J=1,N,1)
      DO 94 I=1,M,1
   94 WRITE (6,606) I,(COEFF(I,J),J=1,N,1)
      WRITE (6,605) (J,J=1,N,1)
```

```
C      .................................................................
C      .                                                               .
C      .  OVERWRITE DATA ARRAY WITH CALCULATED DATA                    .
C      .                                                               .
C      .................................................................
       WRITE (6,604)
       WRITE (6,602) (J,J=1,NPITCH,1)
       DO 20 I=1,NMACH,1
       DO 19 J=1,NPITCH,1
       SUM=0.
       DO 96 I1=1,M,1
       DO 96 J1=1,N,1
    96 SUM=SUM+(COEFF(I1,J1)*DELTA(I,J)**(J1-1))*GAMMA(I,J)**(I1-1)
C      R(J)=((XVEL(I,J)-SUM))/(XVEL(I,J))*100                            *
C      R(J)=((RECF(I,J)-SUM))/(RECF(I,J))*100                            *
       R(J)=  PHI (I,J)-SUM                                              *
C   19 XVEL(I,J)= SUM                                                    *
C   19 RECF(I,J)= SUM                                                    *
    19 PHI (I,J)= SUM                                                    *

    20 WRITE (6,603) I,(R(J),J=1,NPITCH,1)
       WRITE (6,602) (J,J=1,NPITCH,1)



C      .................................................................
C      .                                                               .
C      .  PLOT CALCULATED CALIBRATION SURFACE                          .
C      .                                                               .
C      .................................................................
       CALL SETSM (113,3.)
       DO 81 I=1,NMACH,1
       DO 81 J=1,NPITCH,1
       CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))          **
       IF (J.EQ.1) CALL PLOT (XPLOT,YPLOT,2)
       IF (J.GT.1) CALL PLOT (XPLOT,YPLOT,3)
    81 CONTINUE
       DO 82 J=1,NPITCH,1
       DO 82 I=1,NMACH,1
       CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))          **
       IF (I.EQ.1) CALL PLOT (XPLOT,YPLOT,2)
       IF (I.GT.1) CALL PLOT (XPLOT,YPLOT,3)
    82 CONTINUE


       IFILE(1) = 2HCA
       IFILE(2) = 2HLN
       IFILE(3) = 2HFW
```

```
C      ..........................................................
C      .
C      .  READ DATA FILE CALNEW.
C      .
C      ..........................................................
       CALL OPEN (IDCB,IERR,IFILE,IOPTN,0,28,144)
       IF ( IERR  .LT.  0 ) STOP 0001
       CALL READF (IDCB,IERR,GAMMA,512,LEN,1)
       IF ( IERR  .LT.  0 ) STOP 0002
       CALL READF (IDCB,IERR,DELTA,512,LEN,5)
       IF ( IERR  .LT.  0 ) STOP 0003
       CALL READF (IDCB,IERR,XVEL,512,LEN,9)
       IF ( IERR  .LT.  0 ) STOP 0004
       CALL READF (IDCB,IERR,PHI,512,LEN,13)
       IF ( IERR  .LT.  0 ) STOP 0005
       CALL READF (IDCB,IERR,RECF,512,LEN,17)
       IF ( IERR  .LT.  0 ) STOP 0006
       CALL CLOSE (IDCB,IERR,0)


C      ..........................................................
C      .
C      .  NEXT STEP?
C      .
C      ..........................................................
       WRITE (LI,103) NOCR
       READ  (LI,  *) IDUM
       IF (IDUM.EQ.1) GO TO 91
       IF (IDUM.EQ.2) GO TO 87
       CALL STOPG
       STOP 077
    87 WRITE (LI,104)
       READ  (LI,  *) ALPHAX,ALPHAY,XO,YO
       GO TO 85
       END
```

TURBOPROPULSION LABORATORY

HP9830/21 MX Data Acquisition

Port/Channel Assignments

Test Probe Cal

Run No. ________

Date 6/12/81

New T.C. New dodge probe in 4 1/4" free jet--straight $T_{Ref}$ Probe in pipe

| | S.V. #1 | S.V. # | SCANNER #1 ch | | SCANNER #2 ch | | SCANNER #3 ch | |
|---|---|---|---|---|---|---|---|---|
| 1 | | | 0 | | 0 | | 40 | |
| 2 | PA - PA | | 1 | | 1 | | 41 | |
| 3 | | | 2 | | 2 | | 42 | |
| 4 | Pcal - PA | | 3 | | 3 | | 43 | |
| 5 | | | 4 | | 4 | | 44 | |
| 6 | P1 - PA | | 5 | | 5 | | 45 | |
| 7 | | | 6 | | 6 | $T_{TUN}$ "J" IP | 46 | |
| 8 | P23 - PA | | 7 | | 7 | $T_{TUN}$ "E" IP | 47 | |
| 9 | | | 8 | | 8 | $\Delta T(T_{jet}-T_{pipe})$ | 48 | |
| 10 | P4 - PA | | 9 | | 9 | | 49 | |
| 11 | | | 10 | | 10 | $R7 \times 10^3$ = Mv | 50 | |
| 12 | Pt Tun - PA | | 11 | | 11 | | 51 | |
| 13 | | | 12 | | 12 | | 52 | |
| 14 | | | 13 | | 13 | | 53 | |
| 15 | | | 14 | | 14 | | 54 | |
| 16 | | | 15 | | 15 | | 55 | |
| 17 | $R7 \times 10^5$ = in $H_2O$ | | 16 | | 16 | | 56 | |
| 18 | | | 17 | | 17 | | 57 | |
| 19 | | | 18 | | 18 | | 58 | |
| 20 | | | 19 | | 19 | | 59 | |
| 21 | | | 20 | | 20 | | 60 | |
| 22 | | | 21 | | 21 | | 61 | |
| 23 | | | 22 | | 22 | | 62 | |
| 24 | | | 23 | | 23 | | 63 | |
| 25 | | | 24 | | 24 | | 64 | |
| 26 | | | 25 | P Baro | 25 | | 65 | |
| 27 | | | 26 | $R7 \times 10^4$ = in Hg | 26 | | 66 | |
| 28 | | | 27 | Abs. | 27 | | 67 | |
| 29 | | | 28 | | 28 | | 68 | |
| 30 | | | 29 | | 29 | | 69 | |
| 31 | | | 30 | | 30 | | 70 | |
| 32 | Calib. | | 31 | Calib. | 31 | Calib. | 71 | |
| 33 | inches $H_2O$ | | 32 | inches Hg | 32 | according | 72 | |
| 34 | ≡ volts x $10^5$ | | 33 | ≡ volts x $10^4$ | 33 | to | 73 | |
| 35 | | | 34 | | 34 | thermocouple | 74 | |
| 36 | | | 35 | | 35 | type | 75 | |
| 37 | | | 36 | | 36 | | 76 | |
| 38 | | | 37 | | 37 | | 77 | |
| 39 | | | 38 | | 38 | | 78 | |
| 40 | | | 39 | | 39 | | 79 | |
| 41 | | | | | | | | |
| 42 | | | | | | | | |
| 43 | | | | | | | | |
| 44 | | | | | | | | |
| 45 | | | | | | | | |
| 46 | | | | | | | | |
| 47 | | | | | | | | |
| 48 | | | | | | | | |

Measurements are in Volts

TPL 4/01/81
JH

Table B-I. Calibration Test Instrumentation Connections

| File Name | Mach Number | Pitch Angle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YPRB30 | 1 | -6 | -4 | -2 | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
| YPRB40 | 2 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB45 | 3 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB50 | 4 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB55 | 5 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB60 | 6 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB65 | 7 | " | " | " | " | " | " | " | " | " | " | " | " | " |
| YPRB70 | 8 | " | " | " | " | " | " | " | " | " | " | " | " | " |

Table B-II. Raw Data File Names

| GAMMA | DELTA | XVEL | PHI | RECF |
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| MACH NUMBER = 1 | | | | |
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| 1.254386 | .0658292 | .1327658 | 2.000000 | .9791391 |
| 1.170305 | .0617003 | .1325223 | 4.000000 | .9820595 |
| 1.100437 | .0580034 | .1325223 | 6.000000 | .9916281 |
| 1.025862 | .0547432 | .1325223 | 8.000000 | .9937222 |
| .9521739 | .0504077 | .1322778 | 10.00000 | .9789860 |
| .8744580 | .0465162 | .1327658 | 12.00000 | .9800366 |
| .8034189 | .0432724 | .1330[illegible]9 | 14.00000 | 1.002970 |
| .7531915 | .0407311 | .1332521 | 16.00000 | .9840231 |
| .7008547 | .0377656 | .1327658 | 18.00000 | .9803300 |
| MACH NUMBER = 2 | | | | |
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| 1.487562 | .1311814 | .1768670 | -4.00000 | .8213995 |
| 1.420398 | .1252310 | .1768670 | -2.00000 | .7210634 |
| 1.359802 | .1201603 | .1761789 | 0.000000 | .7959393 |
| 1.277915 | .1128996 | .1765233 | 2.000000 | .7402264 |
| 1.182716 | .1050076 | .1765233 | 4.000000 | .6759887 |
| 1.103961 | .0978161 | .1766954 | 6.000000 | .6942834 |
| 1.012255 | .0905588 | .1768670 | 8.000000 | .7305281 |
| .9511002 | .0852776 | .1765233 | 10.00000 | .6986769 |
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| .7628361 | .0684725 | .1770385 | 16.00000 | .7349200 |
| 7094432 | .0643027 | .1760063 | 18.00000 | .6128314 |
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| 1.448028 | .1696561 | .2078605 | -2.00000 | .9965249 |
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| 1.029982 | .1226227 | .2075839 | 8.000000 | .9929143 |
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| .8778360 | .1056373 | .2079984 | 12.00000 | .9923444 |
| .8124999 | .0982455 | .2084118 | 14.00000 | .9945201 |
| .7604167 | .0919478 | .2078605 | 16.00000 | .9861048 |
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| 1.513386 | .1981208 | .2190310 | -4.00000 | .9908348 |
| 1.455272 | .1878903 | .2186459 | -2.00000 | .9955633 |
| 1.373206 | .1776145 | .2187743 | 0.000000 | .9943811 |
| 1.285714 | .1670249 | .2191589 | 2.000000 | .9965537 |
| 1.196172 | .1547484 | .2192869 | 4.000000 | .9952673 |
| 1.113924 | .1451374 | .2194147 | 6.000000 | .9903313 |
| 1.031496 | .1350634 | .2192869 | 8.000000 | .9918269 |
| .9527559 | .1240047 | .2189025 | 10.00000 | .9911489 |
| .8775511 | .1153392 | .2195426 | 12.00000 | .9939903 |
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| .7593751 | .1002563 | .2197979 | 16.00000 | .9921843 |
| .7138366 | .0937518 | .2187743 | 18.00000 | .9845446 |
| MACH NUMBER = 5 | | | | |
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| .538058 | .2333929 | .2402852 | -4.00000 | .9944553 |
| ..473545 | .2216220 | .2403966 | -2.00000 | .9966950 |
| 1.394422 | .2088067 | .2406194 | 0.000000 | .9914392 |
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| 1.550336 | .2665603 | .2588692 | -4.00000 | .9940820 |
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| 1.411968 | .2361171 | .2576768 | 0.000000 | .9967434 |
| 1.315428 | .2215773 | .2585720 | 2.000000 | .9970744 |
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| 1.641706 | .3195823 | .2796194 | -6.00000 | .9996718 |
| 1.583654 | .3039544 | .2795326 | -4.00000 | .9973757 |
| 1.506256 | .2881830 | .2797930 | -2.00000 | .9979711 |
| 1.427875 | .2704661 | .2797064 | 0.000000 | .9956771 |
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| 1.232625 | .2356273 | .2789234 | 4.000000 | .9931526 |
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| .9731286 | .1869960 | .2785742 | 10.00000 | .9957135 |
| .8975096 | .1728599 | .2790977 | 12.00000 | .9935628 |
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| .530151 | .3221327 | .3004204 | -2.00000 | 1.000791 |
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| .9815592 | .2067599 | .2995806 | 10.00000 | .9960829 |
| .9019120 | .1913724 | .3000392 | 12.00000 | .9951346 |
| .8399669 | .1787676 | .3000390 | 14.00000 | .9957010 |
| .7812500 | .1675020 | .2995039 | 16.00000 | .9938134 |
| .7248764 | .1554063 | .2998099 | 18.00000 | .9951308 |

Table B-III. Reduced Calibration Data

# APPENDIX C. CHROMEL-CONSTANTAN THERMOCOUPLE OUTPUT APPROXIMATION

The relationship between the millivolt output of the Type E (Chromel-Constantan) thermocouple element and the temperature is given by the manufacturer (Omega Engineering, Inc., P.O. Box 4047, Stamford, Connecticut, 06907) from NBS Standard tables. For a range of $0^{\circ}$ to $170^{\circ}$ Fahrenheit the temperature as a function of the voltage was approximated by a second order polynomial using the method of least squares. Figure C1 shows the approximation together with the coefficients for the curve. The second order approximation in Figure C1 was used in the data reduction programs for the probe.

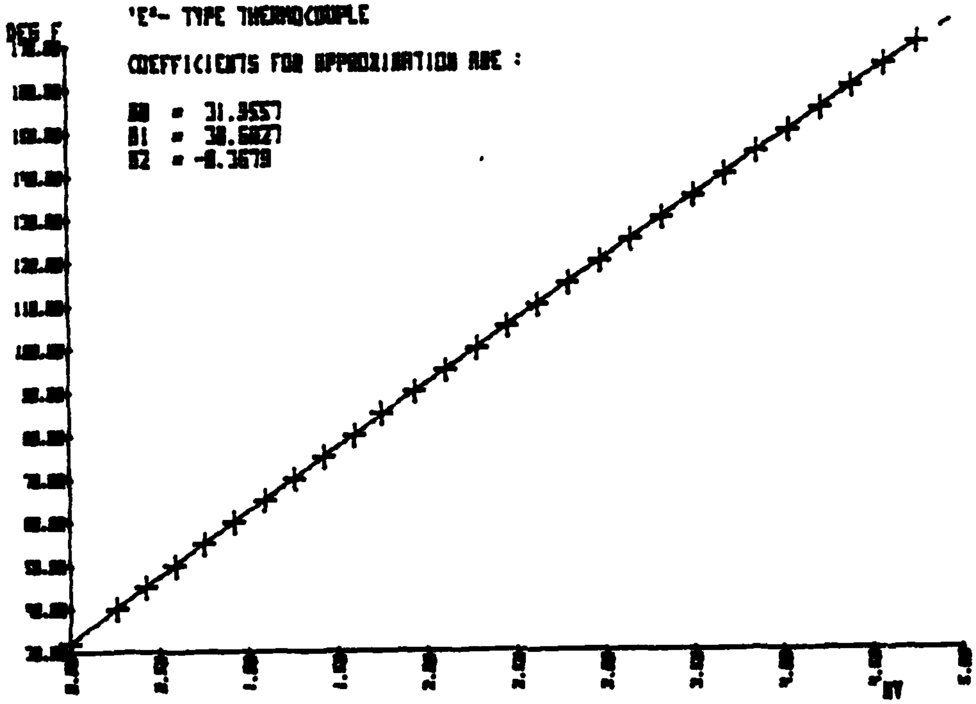



Figure C1. Chromel-Constantan Thermocouple
Voltage Output vs Temperature

## APPENDIX D. PNEUMATIC AVERAGING OF UNSTEADY PRESSURES

Other investigators have questioned whether a pneumatic probe measures the correct time average value of the impact pressure in an unsteady flow (References 7 and 8). It is clear that the possible error in the probe measurement will depend on the relationship between the average pressure level and the unsteady departures therefrom. Weyer, in Reference 7, has measured the magnitude of the error for a particular wave form. In order to get an idea of the error which might be involved if the measurement of P1 was taken to be the time-averaged total pressure, the unsteady pressure distribution in the measuring plane of the probe was observed in the compressor. Figure D1 shows the pressure distribution measured behind the compressor rotor using a simple impact pressure probe incorporating a Kulite semiconductor transducer at the tip. Rotor rotational speed was 15,200 rpm, resulting in a (blade-passing) frequency of 4.56 Khz in the pressure variation. Using the notation of Reference 7, the characteristics of the signal were determined to be the following:

Time average value of the pressure, $\bar{P}_1 = 434"\ H_2O$

Peak-to-peak amplitude of the pressures,

$$(P_{max} - P_{min}) = 2P1_a = 16"\ H_2O$$

Ratio of wave amplitude to mean value, $\frac{2P1_a}{\bar{P}_1} = 0.037$

Figure D2 (from Reference 7) shows the relationship between the error which was measured for a particular pneumatic probe, the frequency, the pressure level and the amplitude of the pressure changes for the particular wave shape indicated in the figure. It is observed that the frequency involved in the present measurements exceeds the range given in Figure D2, and that the value of $2Pl_a/\bar{P}_1$ was also very much smaller.

Similar comparisons between the pressure readings P2 and P3 and corresponding Kulite probe measurements showed that for these sensors $2Pl_a/\bar{P}_1$ was even smaller, thus any error in the averaging of P2 and P3 should be negligible.

An equivalent Kulite probe for P4 did not exist, so that a comparison for this sensor could not be made. However, since the tube for P4 is inclined at an angle to the flow comparable to those of P2 and P3, it can reasonably be assumed that the conclusions are similar.

For operating conditions at higher speeds and flow rates, the above conclusions must be reexamined for the time-varying rotor exit conditions then measured. Whereas the data in Figure D2 suggest that the error becomes small at higher frequencies, it was shown in Reference 9 that measurable errors could occur at 3 - 8 Khz in particular pneumatic systems if the wave form was sufficiently extreme (implying large values of the parameter $2Pl_a/\bar{P}_1$).

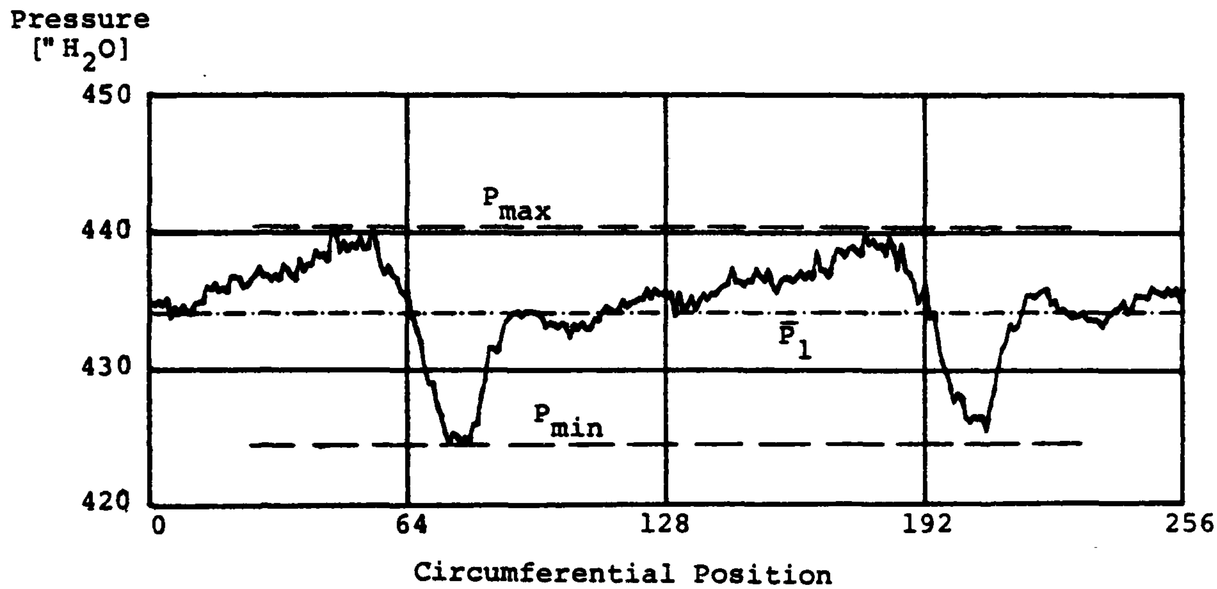
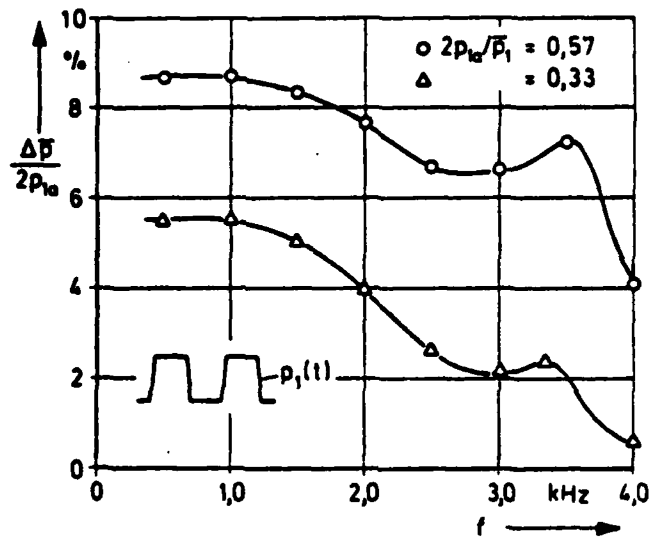



Figure D1. Kulite Probe Measurement of the Pressure Seen by the P1 Sensor at the Rotor Exit




<u>Figure D2</u>. Relative Error in the Pressure Measurement Using Conventional Pneumatic Measurement Systems Depending on the Frequency for Two Different Pressure Amplitudes (measurement hole diameter: 0.028", sharp edge)

(Reproduced from Ref. 7.)

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