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Monterey, California

A Procedure for Obtaining Velocity Vector from Two High Response Impact Pressure Probes

D. Adler and P. M. Taylor

August 1980

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Monterey, California

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A method for experimentally determining the velocity vector for a point in a fluid, downstream of a rotating turboimpeller, is presented. The technique requires four pressure readings from two semiconductor pressure probes and a synchronization system to collect the data. Reduction of the data to the velocity and direction of the fluid particle is performed by the computer program at the end of this report.

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A PROCEDURE FOR OBTAINING VELOCITY VECTOR FROM TWO HIGH RESPONSE IMPACT PRESSURE PROBES

by

D. Adler and P. M. Taylor

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1. Introduction

Experimental knowledge of the flow field generated by rotating turboimpellers is essential for the research and development of turbomachinery. This information is used to refine design methods, develop new flow models which include secondary flow and tip clearance effects, and especially to verify computer programs designed to calculate flow through rotating blade rows.

Laser velocimeters have been used successfully in recent years to measure the flow inside and downstream of rotors (see Ref. 1). Certain disadvantages have become apparent, however. The laser techniques are reliable only in the hands of experienced investigators, the pressure field remains unknown, and usually the measurement of more than two components of the velocity field is complicated and expensive. Furthermore, it is difficult to perform measurements close to walls. Development of alternative techniques to overcome these deficiencies, as well as to achieve redundancy in measuring the flow field, are reasonable and worthwhile tasks.

This report describes a particular method and the computational support necessary to measure the flow field behind an impeller in the stationary, bladeless gap.

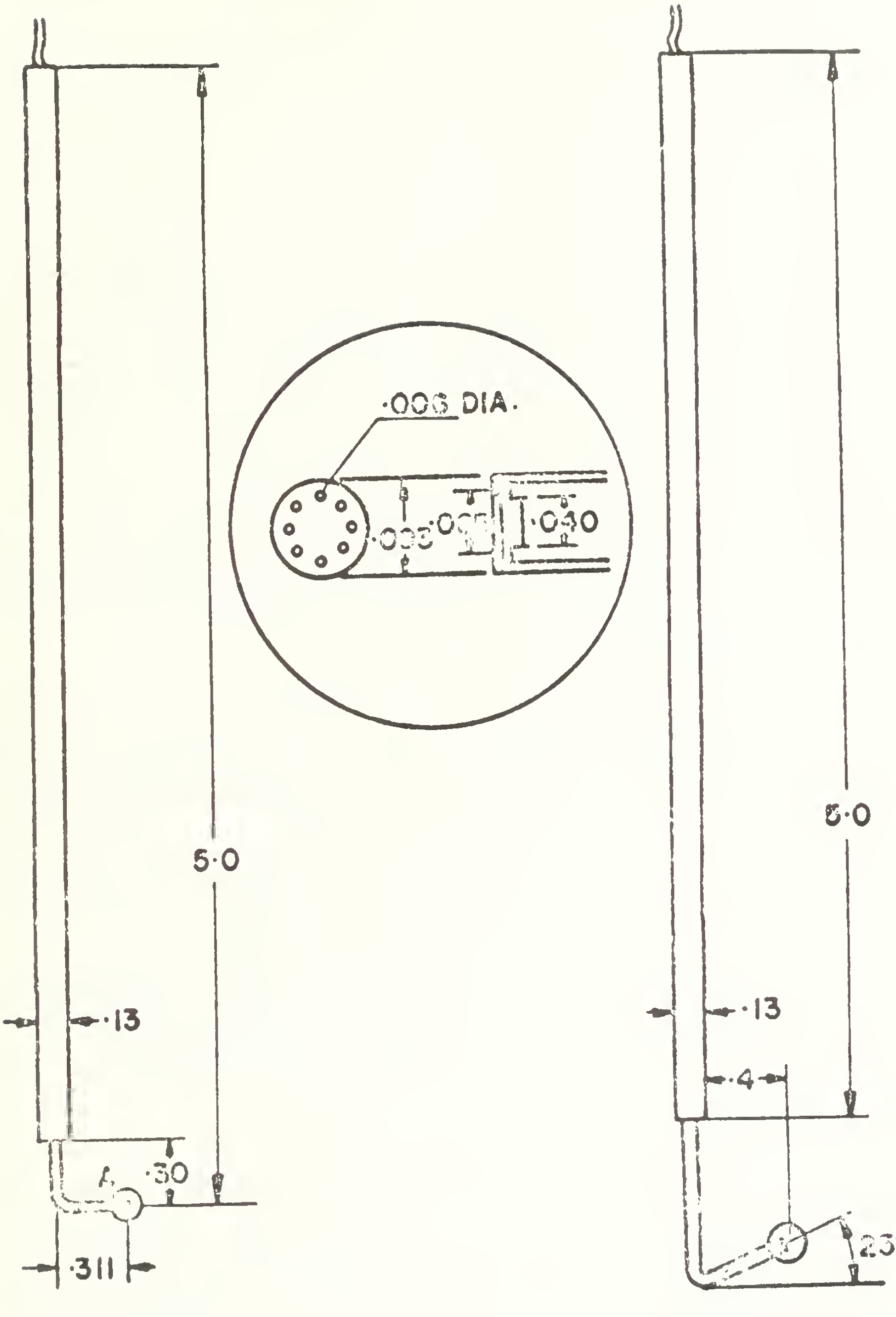
2. Description of Method

The following method requires two semiconductor pressure probes along with a technique for synchronized sampling for determining the fluid velocity vector downstream of a rotor.

The two probes (see Fig. 1) are positioned inside the machine casing so they will, in turn, intercept periodically the same part of the flow leaving a particular passing rotor passage. Each probe reading is sampled when the designated blade passage reaches a desired position relative to the probe. Synchronization is achieved through a suitable method (Ref. 2, 3).

Four quantities are needed to determine the velocity vector: yaw angle, pitch angle, static pressure and total pressure. Accordingly, four measurements must be made to evaluate these unknowns. By rotating the probes about their tips, pressure readings in four different directions can be taken, and the data used to calculate the velocity vector. Computer program VELOCITY, given in Appendix II, was developed to perform the somewhat arduous calculations.

The geometries of the two probes are shown in Fig. 1. Before being used, the probes must be calibrated so their responses to flows coming from different directions are known. A highly directional probe is desired to increase the accuracy in finding the yaw and pitch angles, and consequently the velocity magnitude. The following method is recommended for calibrating each probe -



PROBE TYPE A

PROBE TYPE B

Figure 1. A type and B type probes

1. Establish a steady, controlled flow of fluid, and determine the velocity vector at a certain region of the flow.
2. Position a probe in the flow and rotate the tip so that a sequence of pressure readings are taken for a constant yaw angle and a varying pitch angle. Repeat the procedure at a new yaw angle using the same pitch angles. The result will be an array of pressure readings corresponding to a set grid of yaw and pitch angles (Fig. 2).
3. From the known flow velocity and pressure readings, a coefficient of pressure can be calculated for each angle set:

$$C_p = \frac{p-p_s}{p_T-p_s}$$

where:

C_p = Coefficient of pressure
p = pressure reading
p_s = static pressure of flow
p_T = total pressure of flow

The table of C_p's as well as the yaw and pitch angles which correspond to them are now in the form required for input to program VELOCITY.

The probe calibrations should be insensitive to Mach number and pressure, and are not valid for supersonic flows. Should any significant variations in C_p be observed for different flow conditions, further calibrations will be required and an additional iteration scheme added to the computer program.

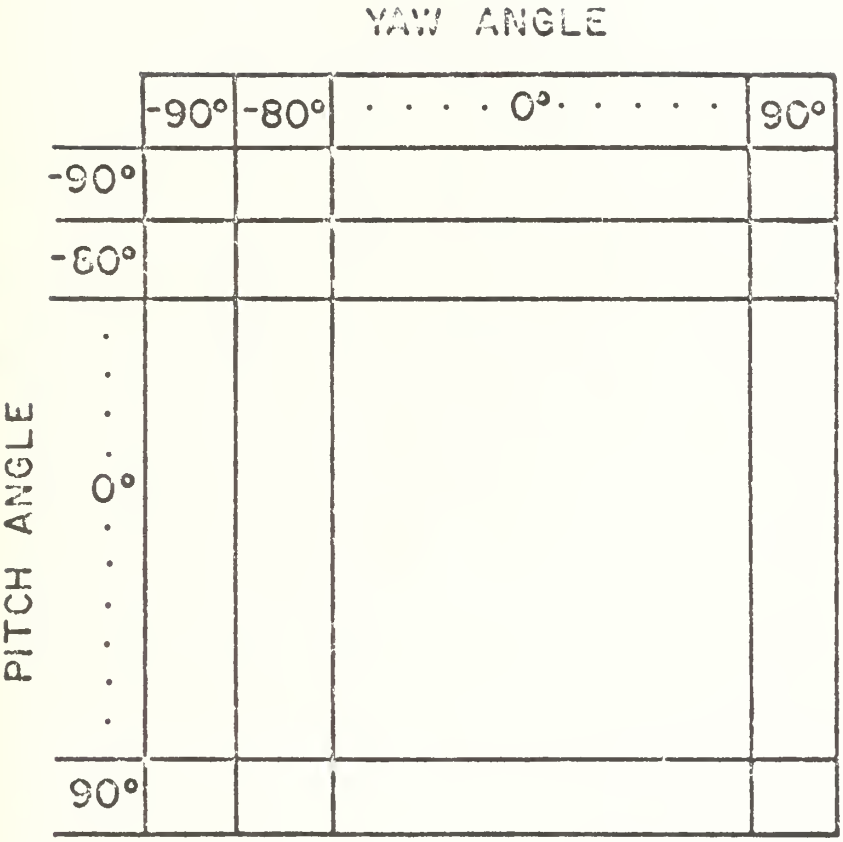


Figure 2. Grid of Yaw and Pitch Angles

Experience with the two-probe technique has shown that excellent results are achieved when a probe type A is rotated to the three positions +25°, 0°, -25° yaw (at 0° pitch), and probe type B is used at 0° yaw (and 25° pitch, Fig. 3).

The two-probe technique is strictly applicable only to periodic flows. However, data obtained on successive rotations of the rotor can be averaged to eliminate non-periodic fluctuations. This was effective for tests reported in Ref. 2., where a single probe was used to establish the peripheral blade-to-blade distribution of flow yaw angle.

It is noted that the method reported here is a further development of that reported earlier in Ref. 6, and overcomes some of the earlier limitations.

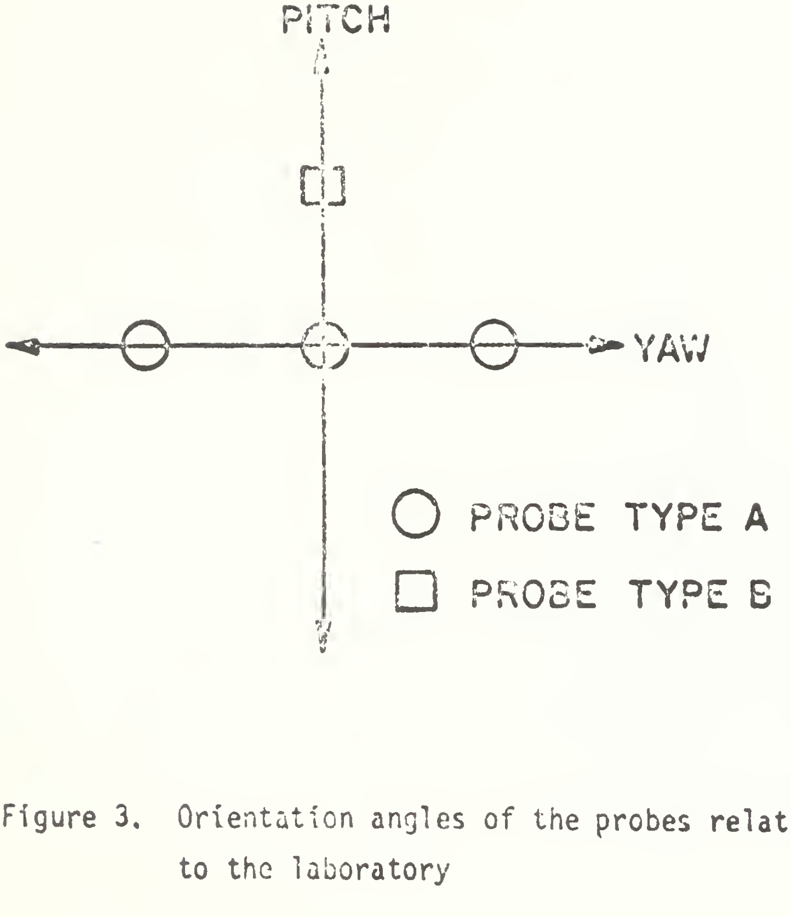


Figure 3. Orientation angles of the probes relative to the laboratory

3. Theory

The velocity vector for a three-dimensional flow can be described with three scalar quantities. The nature of the problem suggests using two angles (a yaw angle and a pitch angle), and the magnitude of the velocity (Fig. 4).

Since pressures and not the velocity are measured, the static and total pressures must first be determined, and Eq. (1) used to evaluate the velocity.

$$\frac{p_T}{p_s} = (1 + \frac{\gamma-1}{2} M^2)^{\gamma/\gamma-1} \qquad (1)$$

Altogether, four unknowns need to be evaluated: the yaw and pitch angles, and the total and static pressures.

Four equations are needed to determine the four unknowns. They are derived from the four pressure readings, each pressure reading having been taken in a different direction as described above. The following equations for the coefficient of pressure can be written:

$$C_{pi} = \frac{p_1-p_s}{p_T-p_s} \qquad i = 1..4 \qquad (2)$$

The C_{pi}'s are a function of the orientation of the probe relative to the flow; i.e., for a given flow the measured C_p's will vary measureably as the probe is turned into and away

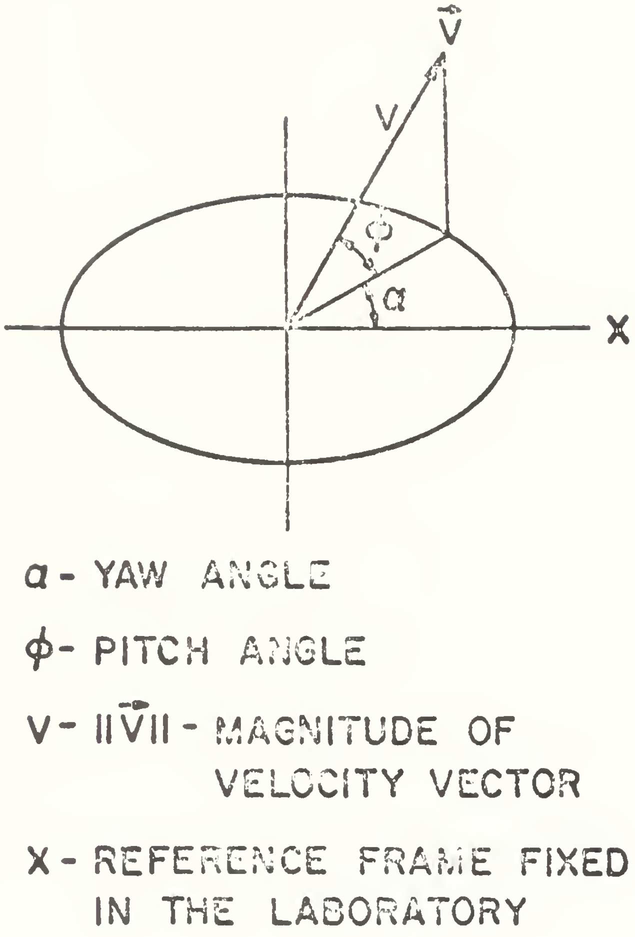


Figure 4. Velocity Vector $\vec{V}$

from the flow. Each "probe"* will have its own C_p characteristics determined experimentally. The result will be a table of C_p vs. yaw and pitch angles for each probe.

$$C_{pi} = \text{function } (\alpha_{Ri} \ , \ \phi_{Ri}) \qquad i = 1..4 \qquad (3)$$

For realistic problems, only one point $(\alpha \ , \ \phi)$ exists where the C_{pi}'s in Eq. (2) will equal the C_{pi}'s of Eq. (3) for the four probes' pressure readings.

The probes' characteristics (C_p's) are in tabular form because they cannot be represented analytically due to the stem effect and production inaccuracies. Therefore, a numerical solution to the problem is required. The procedure chosen for solving the problem is a systematic trial-and-error search process, essentially a convergence scheme on two variables: yaw angle and pitch angle.

The flow direction is assumed to fall within some set of bounds, defining the search area for yaw and pitch (Fig. 5). By setting up a grid of points in this region and checking how well each point satisfies the criteria of equality of coefficients of pressure (C_{pi}'s) calculated with Eqs. (2) and (3), the point with the smallest error can be found and used as a first approximation to the solution. Repeating this procedure, only with a smaller grid and search region, will result in a better approximation. This sequence, represented in Figs. 6

---

* Here, the term "probe" refers to a particular probe type in a particular position.

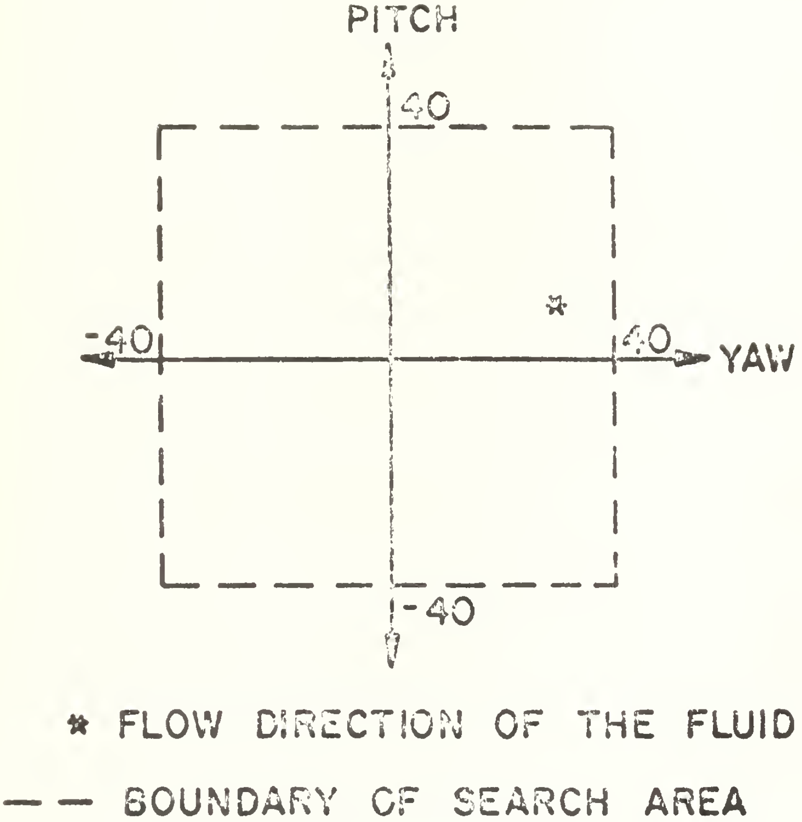


Figure 5. Search area

and 7 is repeated until either the desired accuracy is reached or fatigue sets in. Program VELOCITY, described in the following section, was written to perform these calculations.

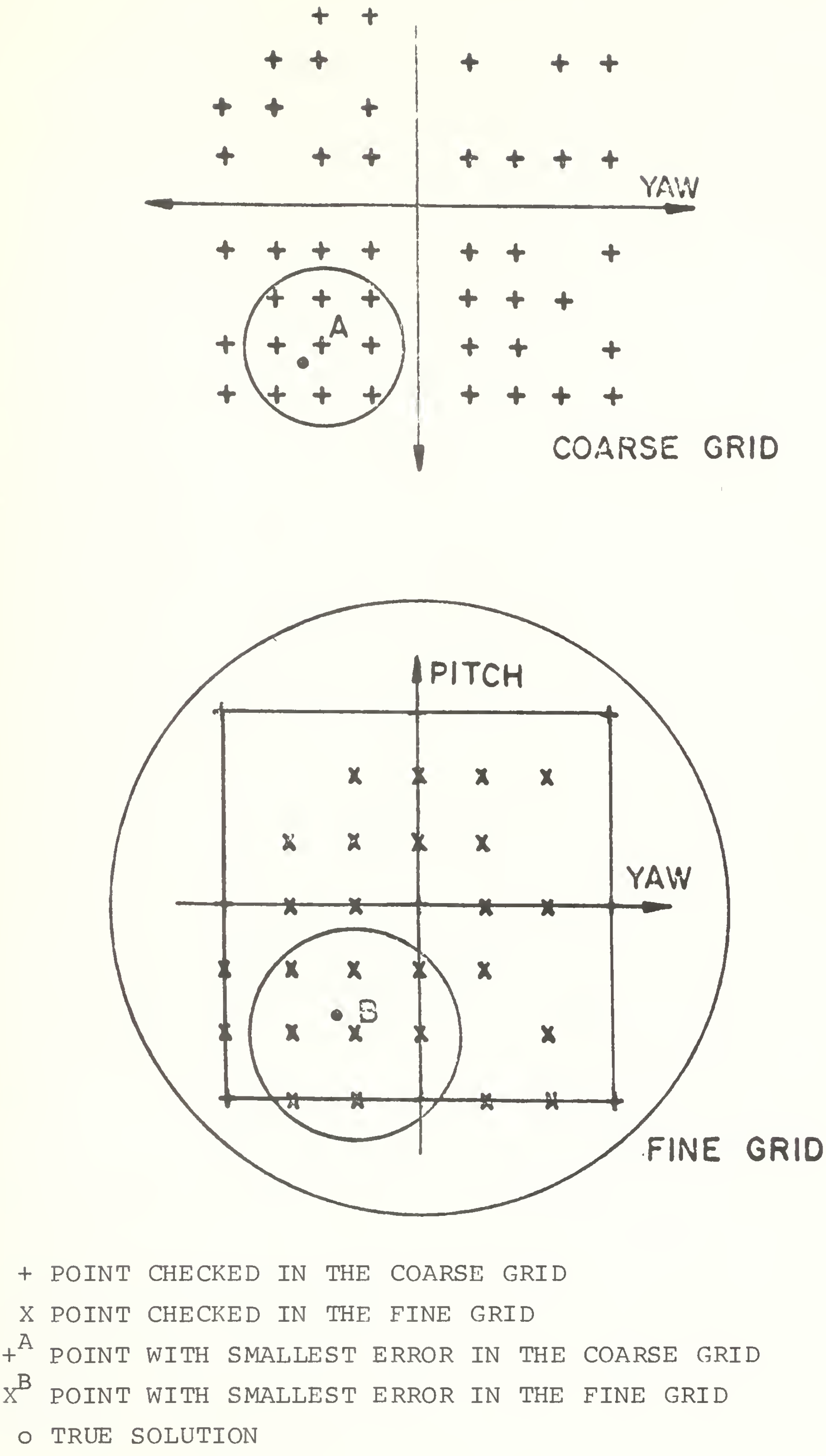


Figure 6. Illustration of the Search Procedure

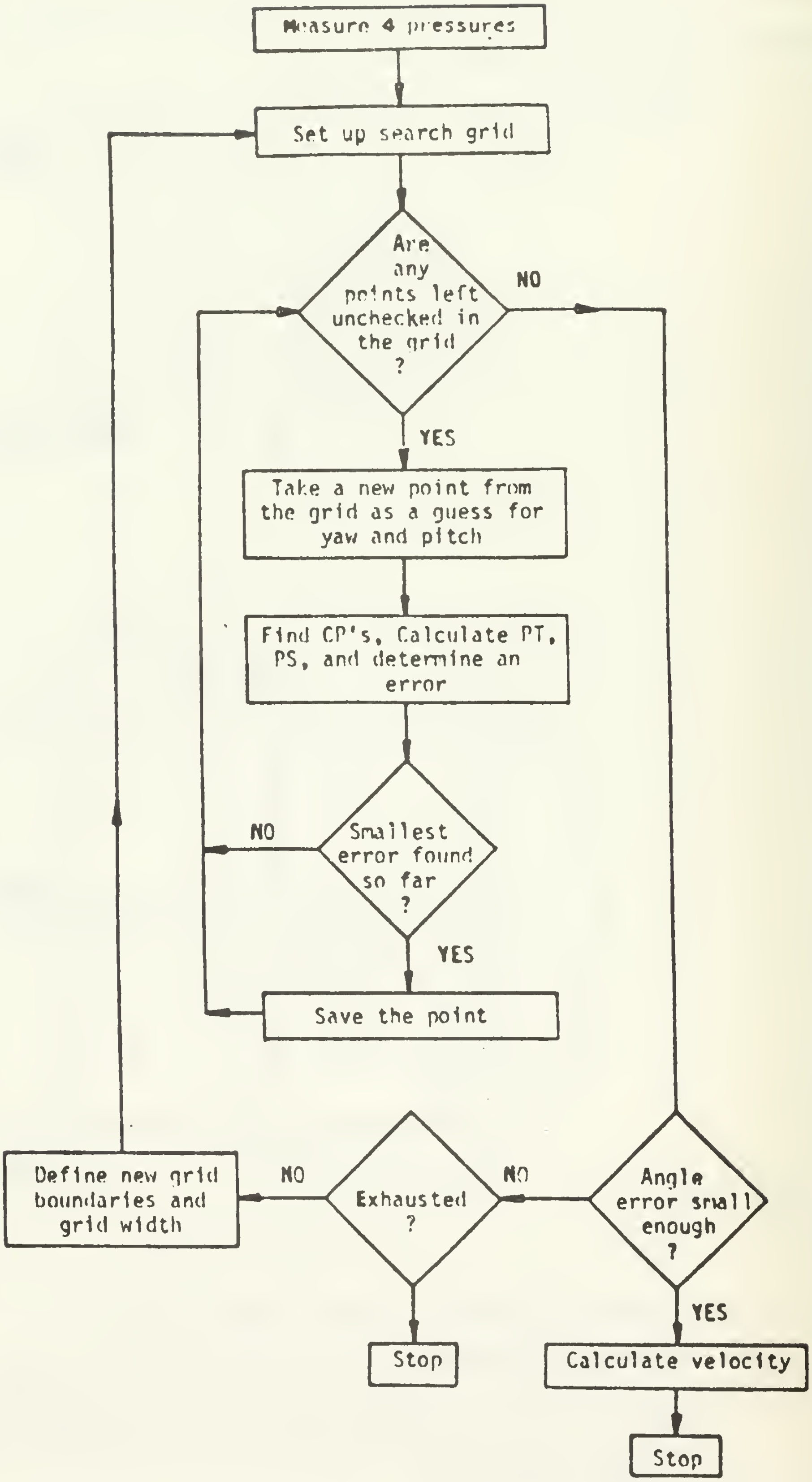


Figure 7. Flow Chart of the Search Procedure

4. Program VELOCITY

Program VELOCITY was written to perform the calculations outlined in the previous section. A description of the program and its subroutines is given below. Fig. 8 summarizes the major sections and organization of the program.

For each run, program VELOCITY reads the calibration tables for the two probes from files outside the program. (Input formatting is discussed in Appendix V.) Subroutine INPUT performs the necessary work, and can be modified to accommodate different input schemes if desired.

The fluid temperature and molecular weight are entered next. These properties are assumed to remain constant throughout the run.

The settings for each pressure reading are read next. A setting contains the following data: probe type (A or B), yaw angle setting, and pitch angle setting. Again, these settings will not change for the duration of the run.

Finally, the four pressure readings are entered.

The first scan is initiated and covers the entire region of expected flow directions, -40° to $+ 40^\circ$ in both yaw and pitch angles in the present case. Points are chosen every 5°, each point representing a unique pair of yaw and pitch angles. For each point, a static pressure, a dynamic pressure, and an error are calculated by the scheme described below.

A point, say $(\alpha\ , \phi)$ is tested; i.e., a test is performed to prove whether assumed flow, oriented α degrees yaw and ϕ

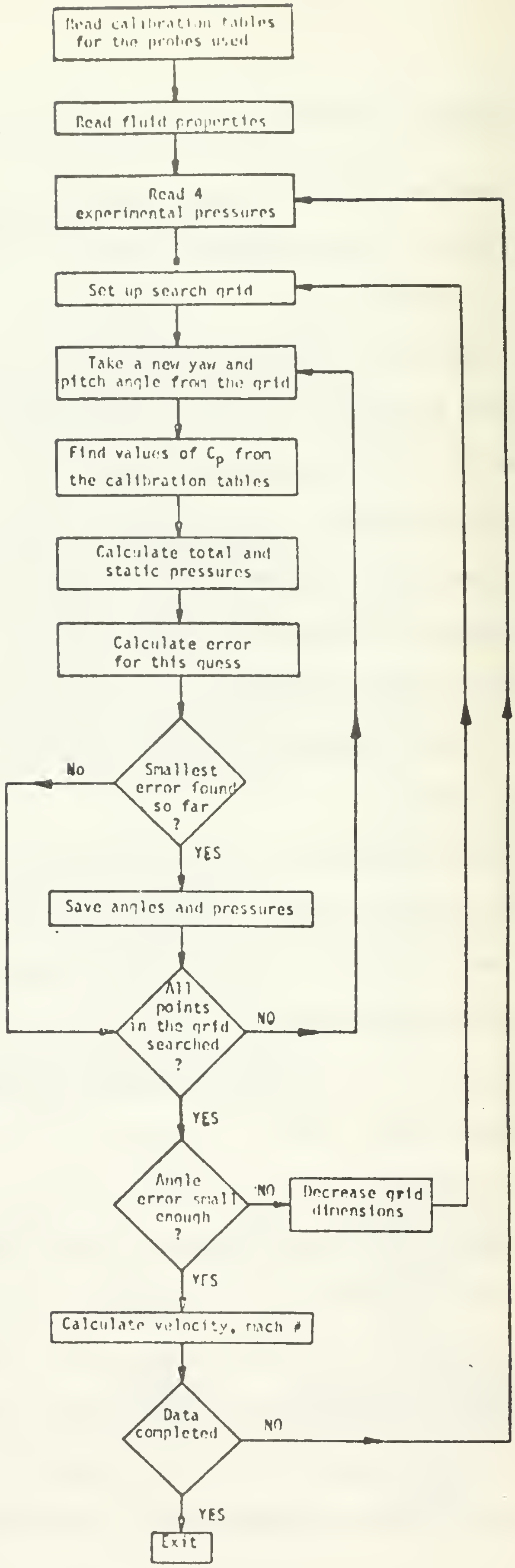


Figure 8. Flow Chart of Program VELOCITY

degrees pitch relative to the laboratory reference frame, corresponds to the four pressure readings. The direction of the flow relative to each probe setting is calculated. For probe setting i, oriented at (α_i, ϕ_i) relative to the laboratory, the assumed flow approaches at a relative angle of:

$$\alpha_{Ri} = \alpha - \alpha_i \tag{4}$$

$$\phi_{Ri} = \phi - \phi_i \tag{5}$$

where (α_{Ri}, ϕ_{Ri}) are the yaw and pitch angles respectively of the assumed flow relative to probe setting i. The C_p calibration table for the probe used in setting i is consulted and a $C_p(\alpha_{Ri}, \phi_{Ri})$ returned. Subroutine CPCAL locates or calculates the desired C_p values in the table. The scheme used in CPCAL is a search technique to find the values of yaw and pitch surrounding the desired point, and then a linear interpolation over these four points as shown in Fig. 9.

Eq. (2) can be rewritten in the form

$$(C_{pi})p_T + (1-C_{pi})p_s = p_i \qquad i = 1..4 \tag{6}$$

the only unknowns being p_T and p_s. With four equations and two unknowns, the problem will be inconsistent unless the true α and ϕ were chosen. Accordingly, the following schemes were used to evaluate p_s, p_T and an error.

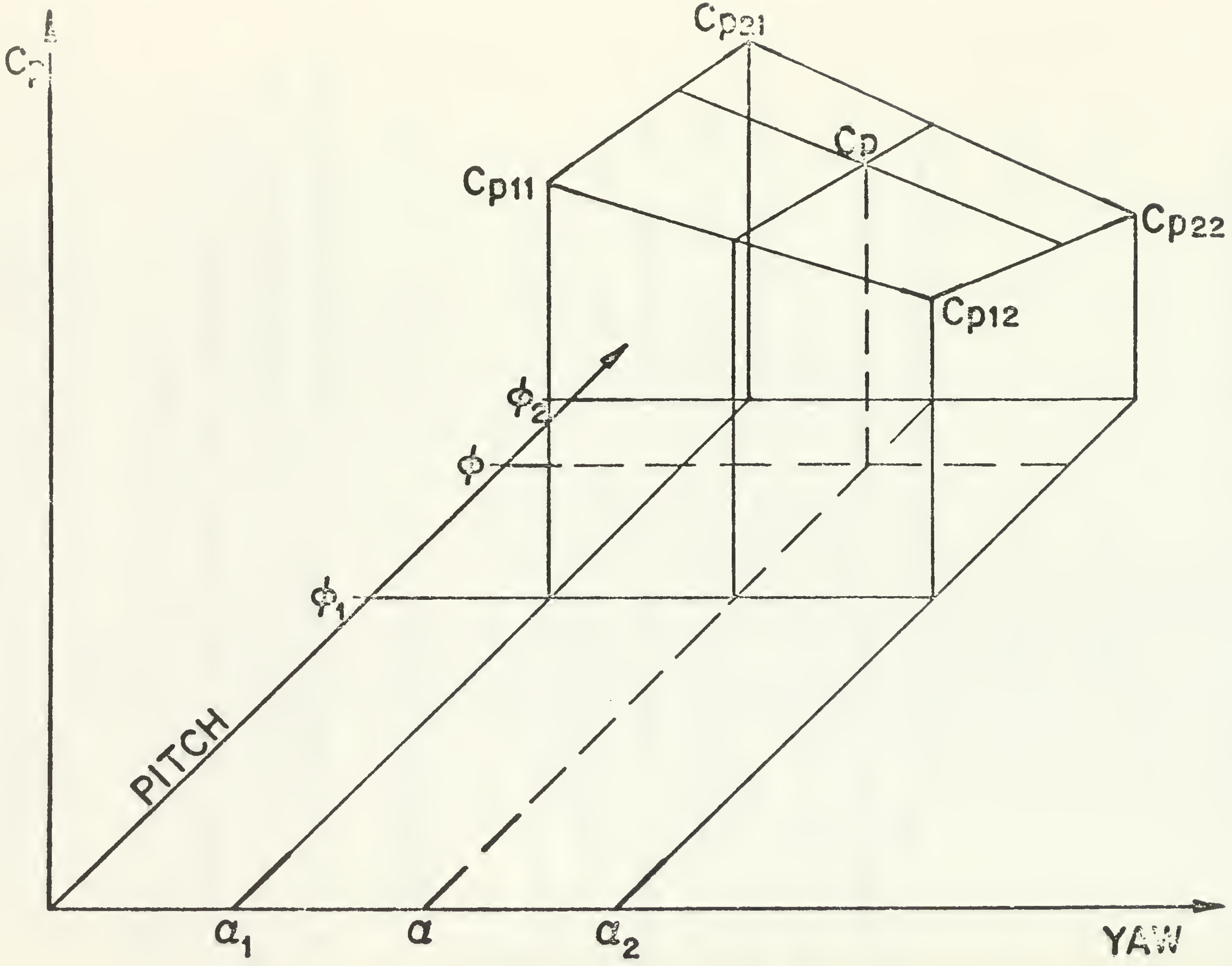


Figure 9. Linear interpolation between four points to find C_p

Define:

$$\underline{C_p} = \sum_{i=1}^{4} C_{p_i} \tag{7}$$

$$\underline{p} = \sum_{i=1}^{4} p_i \tag{8}$$

C_{p_m} = minimum of $(C_{p_1}, C_{p_2}, C_{p_3}, C_{p_4})$

$p_m = p_i$ corresponding to the C_{p_m} chosen above.

$$(C_p)p_T + (4-C_p)p_s = p \tag{9}$$

and also

$$(C_{p_m})p_T + (1-C_{p_m})p_s = p_m \tag{10}$$

These two equations can be solved for p_T and p_s :

$$p_T = \frac{\underline{p}(1-C_{p_m}) - p_m(4-\underline{C_p})}{C_p - 4C_{p_m}} \tag{11}$$

$$p_s = \frac{\underline{C_p}(P_m) - C_{p_m}(\underline{p})}{\underline{C_p} - 4C_{p_m}} \tag{12}$$

$$\text{Error} = \sum_{i=1}^{4} \text{ABS}(C_{p_i} - \frac{p_i-p_s}{p_T-p_s})/4 \tag{13}$$

These schemes were chosen for two reasons:

1) They used all the available data to derive an error which would effectively represent the accuracy of the guess.

2) No singularities in the calculations can occur except for the case of four equal C_p's (which physically represents trying to find an intersection point among four parallel lines). If the measurements are taken in the suggested directions, this anomalous point will not appear.

For each point guessed in the initial scan, an error is calculated and the point with the smallest error is saved. A new, finer search grid is composed using this point as the new origin. The boundaries of the new grid are the points from the old grid which were closest to this new origin. Referring to Figure 10, if x represents the true solution, the new boundary would be formed by the points marked B-I, and the new grid-width would be one third as large. This factor was chosen to minimize the number of guess evaluations. (The first scan contains a large number of guesses in order to correctly isolate the general region of the solution).

The search procedure is performed on each new grid, and the process repeated until the grid width is less that 0.5°. After the final scan, the best guess is used to calculate the flow velocity and Mach number. The results are printed out and the next four pressures requested. If no values are entered (end of data set), the program ends.

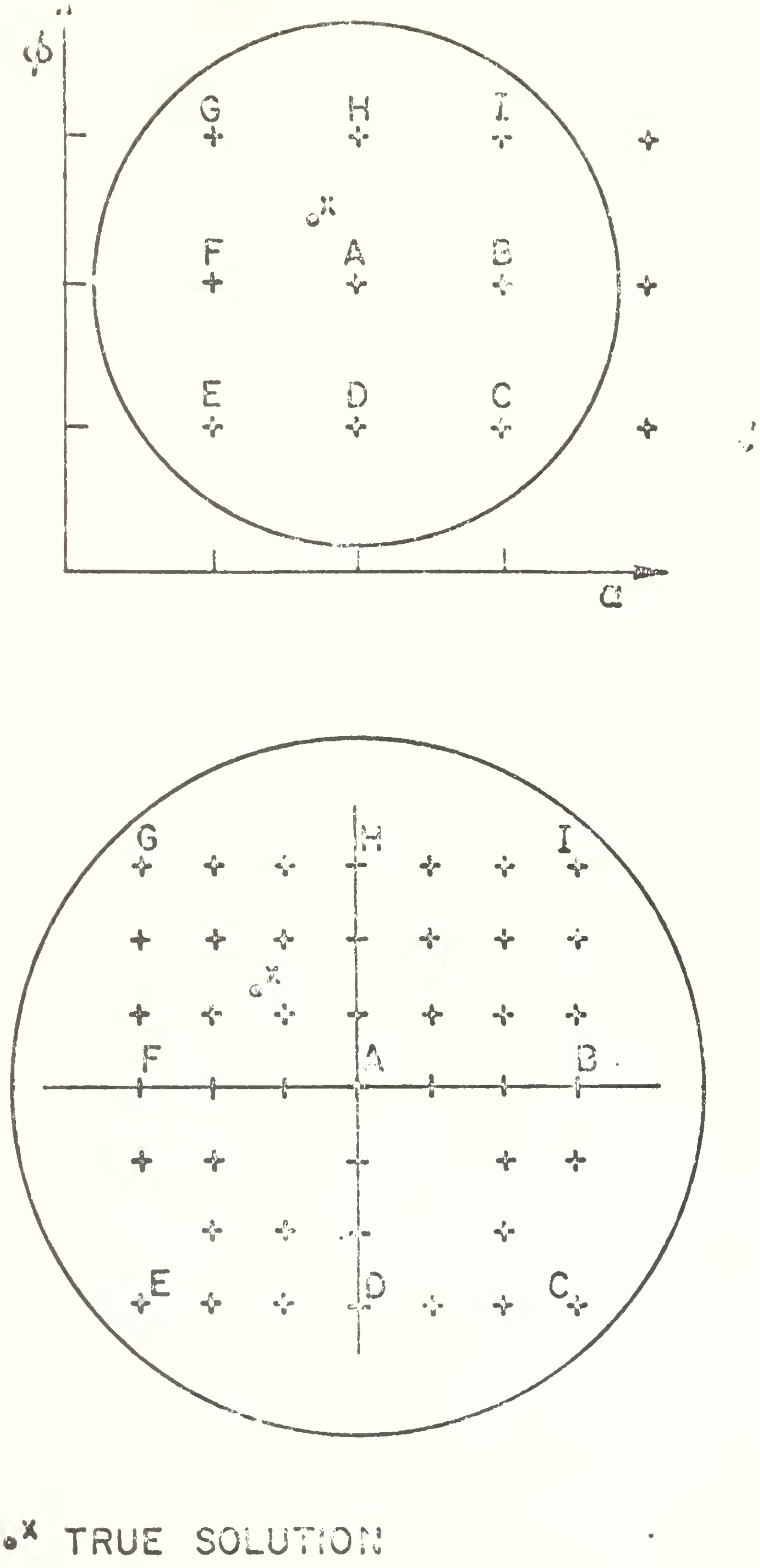


Figure 10. Defining new grid boundaries from the nearest neighbors of the point with the smallest error

5. Discussion

Extensive tests with program VELOCITY have led to the observations and suggestions listed below:

1. Excellent results are achieved when the probe settings are at (yaw, pitch) angles of (-25,0), (0,0), (25,0) and (0,25) degrees. This corresponds to a rotation of probe type A from -25° to 0° to 25°, and one reading from probe type B at (0,25). Poor results were achieved for the symmetric case of readings at (± 25,0) and 0,± 25) degrees.
2. Highly directional probes increase the accuracy of the procedure, especially if the C_p variation is significant when the flow is nearly head-on To achieve these characteristics, the following design suggestion is offered. The probe can be formed with a spherical tip, the pressure tap being located in the center. To prevent damage to the sensitive transducer located behind the pressure tap and to improve the frequency response, the void between the pressure tap face and the transducer should be filled with an an appropriate liquid and the opening of the pressure tap sealed with a thin, low-inertia membrane.
3. Higher accuracy naturally results if more calibration points are taken for the probes' C_p tables. The linear interpolation scheme can be replaced by the second order scheme offered in Appendix 5 (if no significant

anomalies occur in the calibrations), the second order method requiring fewer calibration points (say every 15^{o}) than the linear method (every 5^{o} or 10^{o}).

4. The use of **two probes** of relatively simple geometry in periodic flow is less cumbersome and complex than the use of five-hole probes (Ref. 4).

Notation Summary

C_p - Coefficient of pressure
C_p is a function of α and ϕ , $C_p = C_p\ (\alpha\ ,\ \phi)$

C_{pi} - Coefficient of pressure for probe setting i
$C_{pi} = C_p(\alpha_{Ri}\ ,\ \phi_{Ri})$

$\underline{C_p}$ - Sum of the four C_{pi}'s

C_{p_m} - Minimum of the four C_{pi}'s

$C_{p_{11}}$ - $C_p(\alpha_1\ ,\ \phi_1)$

$C_{p_{12}}$ - $C_p(\alpha_1\ ,\ \phi_2)$

$C_{p_{21}}$ - $C_p(\alpha_2\ ,\ \phi_1)$

$C_{p_{22}}$ - $C_p(\alpha_2\ ,\ \phi_2)$

P - Pressure (all pressures are absolute)

P_i - Pressure read from probe setting i

P_s - Static pressure

P_T - Total pressure (stagnation pressure)

$\underline{p}$ - Sum of the four pressures (Pi's)

P_m - Pressure at the setting where C_{p_m} occurred (i.e., $P_m = P_i$, where $i = m$, defined in C_{p_m})

V - Velocity magnitude of the fluid particle

$\overline{V}$ - Fluid velocity vector

α , ϕ - Yaw, Pitch angles

α_i , ϕ_i - Yaw, Pitch angles for probe setting i

α_{Ri} , ϕ_{Ri} - Yaw, Pitch angles for the assumed flow direction direction relative to the probe setting

ρ - fluid density

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PPENDIX I - PROGRAM VELOCITY

```
C
C                          VELOCITY AND DIRECTION
C          OF A FLUID AT A POINT USING FOUR PRESSURES
C                                                            PAUL TAYLOR
C
C         GIVEN THE PRESSURES SENSED BY PROBES IN FOUR
C   DISTINCT DIRECTIONS, AND KNOWING THE CHARACTERISTICS OF THE
C   PROBES AND FLUID PROPERTIES.  THE FLUID VELOCITY, DIRECTION,
C   AND TOTAL AND STATIC PRESSURE ARE CALCULATED.
C
C
      DIMENSION PRB1(19,2),PRB2(19,2),CP1(19,19),CP2(19,19)
      DIMENSION ALP(4),PHI(4),NPRB(4),PRESS(4),CP(4)
      REAL MACH
C
C   SUBROUTINE INPUT RECEIVES THE NECESSARY PROBE CHARACTERISTICS
C   FOR THE TWO PROBES -- MATRICES PRB1 AND PRB2 RECEIVE
C   THE AXIS (ALPHA AND PHI) VALUES, AND CP1 AND CP2 RECEIVE
C   THE CP VALUES FOR PROBES 1 AND 2 RESPECTIVELY.
C
      CALL INPT(NALPH1,NPHI1,PRB1,CP1,IER)
      CALL INPT(NALPH2,NPHI2,PRB2,CP2,IER)
      IF(IER.NE.0) GOTO 1000
C
C     READ THE FOLLOWING FLUID PROPERTIES:
C
C   WM     = MOLECULAR WEIGHT OF THE FLUID
C   GAMMA  = RATIO OF SPECIFIC HEATS OF THE FLUID
C   TC     = TEMPERATURE DEGREES CENTIGRADE OF THE GAS
C   COMP   = ESTIMATE OF THE COMPRESSIBILITY FACTOR
C
   50 READ(5,5010) WM,GAMMA,TC,COMP
 5010 FORMAT(4F10.4)
      RGAS = 8314./WM
      WRITE(7,7700) WM,GAMMA,TC,COMP
 7700 FORMAT(' FLUID PROPERTIES :',//,' MOLECULAR WT =',T30,F8.4,/,
     1       ' RATIO OF SPECIFIC HEATS =',T30,F8.4,/,' TEMPERATURE',
     2       ' DEG C =',T30,F8.4,/,' COMPRESSIBILTY FACTOR =',T30,F8.4)
      WRITE(6,6000)
 6000 FORMAT('1        STATIC       TOTAL',12X,'YAW     PITCH',5X,
     1       'VELOCITY    MACH',/,3X,'PRESS (PA)    PRESS(PA)',
     2      8X,'ANGLE    ANGLE',6X,'(M/SEC)   NUMBER',//)
      WRITE(7,7710)
 7710 FORMAT(///,' PROBE         YAW         PITCH        PRESSURE',/,
     1       '  TYPE    SETTING    SETTING       READ (PA)',//)
C
C
C   ***** START LOOP *****
C
C
C   READ IN THE EXPERIMENTAL DATA FOR THIS DETERMINATION
C
C   NPRB(I)   = THE PROBE TYPE (EITHER 1 OR 2) OF PROBE SETTING I
C   ALP(I)    = ALPHA (YAW) ANGLE OF PROBE SETTING I
C   PHI(I)    = PHI (PITCH) ANGLE OF PROBE SETTING I
C   PRESS(I)  = PRESSURE READ BY PROBE SETTING I
C
C   ALPI, PHII, NPRBI  CONTAIN THE NEW VALUES OF THE YAW, PITCH,
C   AND PROBE TYPE FOR EACH SETTING. IF THE VALUE READ FOR THE PROBE
C   TYPE IS ZERO (NPRBI=0), THEN THE PROBE SETTING FOR THE PREVIOUS
C   TRIAL IS USED.  NO DEFAULT VALUES ARE PROVIDED, SO THE FIRST
C   TRIAL MUST CONTAIN THE PROBE SETTINGS.
C
   10 DO 20 I=1,4
      READ(5,5020,END=999) PRESS(I),ALPI,PHII,NPRBI
 5020 FORMAT(3F10.4,I1)
      IF(NPRBI.EQ.0) GOTO 15
      ALP(I)=ALPI
      PHI(I)=PHII
      NPRB(I)=NPRBI
   15 WRITE(7,7720) NPRB(I),ALP(I),PHI(I),PRESS(I)
 7720 FORMAT(1X,I3,2X,2F10.2,F14.2)
   20 CONTINUE
      WRITE(7,7730)
 7730 FORMAT(//)
C
C   ESTABLISH SCANNING RANGE, GRID WIDTH, AND INITIALIZE ERROR
C
```

VELOCITY

```
C   AMIN, AMAX = MINIMUM, MAXIMUM YAW ANGLES
C   PMIN, PMAX = MINIMUM, MAXIMUM PITCH ANGLES
C   DEL        = GRID WIDTH
C   ERRMIN     = MINIMUM ERROR FOUND SO FAR
C
      AMIN=-40.
      AMAX=40.
      PMIN=-40.
      PMAX=40.
      DEL=5.
  150 ERRMIN=100000.
C
C           START SCAN PROCEDURE
C
C   X = YAW ANGLE GUESS
C   Y = PITCH ANGLE GUESS
C
      Y=PMIN
  160 X=AMIN
C
C   CPSUM  = STORES THE SUM OF THE FOUR CP'S READ FROM BY CPCAL
C   PRSSUM = STORES THE SUM OF THE FOUR INPUT PRESSURES
C   CPMIN  = STORES THE MINIMUM CP VALUE FOR THIS GUESS
C   PRMIN  = STORES THE PRESSURE CORRESPONDING TO THE MINIMUM CP
C
  170 CPSUM=0.
      PRSSUM=0.
      CPMIN=5.
C
C   START THE ANALYSIS BY FINDING THE CP VALUES FROM THE TABLE CPCAL,
C   AND EVALUATING CPSUM, CPMIN, AND PRSSUM
C
      DO 200 K=1,4
      XR=X-ALP(K)
      YR=Y-PHI(K)
      IF(NPRB(K).EQ.1) CALL CPCAL(NALPH1,NPHI1,PRB1,CP1,XR,YR,CP(K),IFL)
      IF(NPRB(K).EQ.2) CALL CPCAL(NALPH2,NPHI2,PRB2,CP2,XR,YR,CP(K),IFL)
      IF(IFL.NE.0) GOTO 250
      CPSUM=CPSUM+CP(K)
      PRSSUM=PRSSUM+PRESS(K)
      IF(CPMIN.LT.CP(K)) GOTO 200
      CPMIN=CP(K)
      PRMIN=PRESS(K)
  200 CONTINUE
C
C   FROM THE ABOVE DATA, CALCULATE A TOTAL AND STATIC PRESSURE
C
C   PTT = A CHARACTERISTIC TOTAL PRESSURE FOR THIS YAW,PITCH
C   PSS = A CHARACTERISTIC STATIC PRESSURE FOR THIS YAW,PITCH
C
      DENOM=CPSUM-4.*CPMIN
      PTT=( PRSSUM*(1.-CPMIN) - PRMIN*(4.-CPSUM) )/DENOM
      PSS=( CPSUM*PRMIN - PRSSUM*CPMIN)/ DENOM
C
C   CALCULATE A CHARACTERISTIC ERROR AND COMPARE WITH THE
C   PREVIOUSLY FOUND SMALLEST ERROR
C
      IF(PTT.LE.PSS) GOTO 250
      ERRR=0.
      DO 225 IR=1,4
  225 ERRR=ERRR + ABS(CP(IR) - (PRESS(IR)-PSS)/(PTT-PSS) )
      ERRR=ERRR/4.
      IF(ERRR.GE.ERRMIN) GOTO 250
C
C   THIS POINT HAS THE SMALLEST ERROR FOUND SO FAR, SO IT IS SAVED
C   AND REPLACES THE PREVIOUSLY FOUND BEST POINT
C
C   PS, PT = THE BEST STATIC, TOTAL PRESSURE FOUND
C   XMIN, YMIN = THE YAW, PITCH ANGLES WHERE THE MINIMUM ERROR WAS FOUND
C
      ERRMIN=ERRR
      PS=PSS
      PT=PTT
      XMIN=X
      YMIN=Y
C
  250 X=X+DEL
      IF(X.LE.AMAX) GOTO 170
```

VELOCITY

```
  300 Y=Y+DEL
      IF(Y.LE.RMAX) GOTO 160
C
C  WE CONTINUE REDUCING THE GRID SIZE UNTIL THE ERROR IN THE
C  ANGLE REACHES 0.5 DEGREES
C
      IF(DEL.LE.0.501) GOTO 350
C
C  WE REPEAT THE PROCEDURE AROUND THE  BEST POINT FOUND SO FAR
C  EXCEPT USING A GRID 1/3 AS WIDE
C
      AMIN=XMIN-DEL
      AMAX=XMIN + DEL
      RMIN=YMIN - DEL
      RMAX=YMIN + DEL
      DEL = DEL/3.
      GOTO 150
C
C  CALCULATE THE DESIRED QUANTITIES, FIRST CHECKING FOR THESE ERRORS:
C     IFL # 0 MEANS THE RANGE OF THE CALIBRATION TABLE WAS EXCEEDED
C            IN THE LAST SCAN
C     STATIC PRESSURE <= 0, THE FLUID VELOCITY REQUIRES A POSITIVE
C                   STATIC PRESSURE
C
C
C  RHO = FLUID DENSITY  (KG/M**3)
C  VEL = FLUID VELOCITY (M/SEC)
C  CO  = SONIC VELOCITY OF FLUID (M/SEC)
C  MACH= FLUID MACH NUMBER
C
  350 IF(IFL.NE.0) WRITE(6,7000)
 7000 FORMAT('-*** WARNING THE RANGE OF THE CALIBRATION ',
     1       'TABLE MIGHT NOT HAVE BEEN SUFFICIENT TO ',
     2       'ALLOW PROPER CALCULATIONS')
      IF(PS.LE.0.) GOTO 450
      RHO = PS/(RGAS*COMP*(TC+273.16))
      MACH=SQRT(((PT/PS)**((GAMMA-1.)/GAMMA)-1.)/((GAMMA-1.)/2.))
      CO = SQRT(GAMMA*RGAS*(TC+273.16))
      VEL=CO*MACH
      WRITE(6,6010) PS,PT,XMIN,YMIN,VEL,MACH
 6010 FORMAT(1X,2F12.2,5X,2F8.2,5X,F8.2,F8.3)
      GOTO 10
C
C  A NEGATIVE STATIC PRESSURE HAS BEEN FOUND
C
  450 WRITE(6,7010) PS,PT,XMIN,YMIN
 7010 FORMAT(' NEGATIVE STATIC PRESSURE',/,
     1       ' PS,PT,YAW,PITCH :',4F12.2)
      GOTO 10
 1000 WRITE(6,7030)
 7030 FORMAT(' AN INPUT ERROR OCCURRED WHILE ',
     1       'READING IN THE PROBE CHARACTERISTICS')
  999 STOP
      END
```

VELOCITY

```
C
C
C           SUBROUTINE INPT
C
C  THIS SUBROUTINE READS IN THE DATA FOR THE PROBE CHARACTERISTICS.
C  IT CAN BE CHANGED TO ANOTHER SUITABLE FORM IF REQUIRED.
C
C     NA, NP    = NUMBER OF POINTS ON THE ALPHA, PHI AXIS
C     PRB(*,1) = ALPHA VALUES ON THE AXIS OF THE CALIBRATION
C                 TABLE
C     PRB(*,2) = PHI VALUES ON THE AXIS OF THE CALIBRATION
C                 TABLE
C     CP(NA,NP)= MATRIX CONTAINING THE VALUES OF CP FOR THE
C                 PARTICULAR PROBE
C
C
      SUBROUTINE INPT(NA,NP,PRB,CP,IER)
      DIMENSION PRB(19,2), CP(19,19)
      READ(8,8000,END=999) NA,NP
 8000 FORMAT(2I4)
      READ(8,8010,END=999) (PRB(I,1),I=1,NA)
      READ(8,8010,END=999) (PRB(J,2),J=1,NP)
 8010 FORMAT(10F9.2)
      READ(8,8020,END=999) ((CP(I,J),J=1,NP),I=1,NA)
 8020 FORMAT(10F8.5)
      IER=0
      RETURN
C
C       THERE HAS BEEN AN ERROR WHILE INPUTTING THE DATA,
C       SO AN ERROR FLAG, IER, IS SET =1
C
  999 IER=1
      RETURN
      END
```

VELOCITY

```
C
C
C          SUBROUTINE CPCAL
C
C   NA,NP = # OF ALPHA AND PHI ANGLES IN THE CP CALIBRATION
C   A(NA) = VALUES OF THE ALPHAS FOR THE CALIBRATION TABLE (YAW ANGLES)
C   P(NP) = VALUES OF THE PHIS FOR THE CALIBRATION TABLE (PITCH ANGLES)
C   CP(NA,NP) = VALUE OF CP FOR EACH ANGLE SET ( A(NA),P(NP) )
C   X       = DESIRED ALPHA ANGLE
C   Y       = DESIRED PHI ANGLE
C   Z       = CALCULATED CP
C   IFLAG = ERROR FLAG
C
C   THIS PROGRAM ESTIMATES THE VALUE OF CP FOR A GIVEN ANGULAR INPUT
C   (ALPHA, PHI)  USING A LINEAR DOUBLE INTERPOLATION SCHEME BETWEEN
C   THE KNOWN VALUES OF CP FOR ANGLES ABOVE AND BELOW THE DESIRED ANGLE
C
C
      SUBROUTINE CPCAL(NA,NP,PRB,CP,X,Y,Z,IFLAG)
      DIMENSION PRB(NA,2),CP(NA,NP)
C
C   START THE SEARCH FOR THE ALPHA VALUES ABOVE AND BELOW THE
C   DESIRED YAW ANGLE
C
C            MXA, MNA = STORES THE ENTRIES TO PRB AND CP FOR THE ANGLES
C                 ABOVE, BELOW THE DESIRED ANGLE
C            AP, AN = THE ALPHA ANGLES ABOVE, BELOW THE DESIRED ANGLE
C
      DO 10 I=2,NA
      MXA=I
      MNA=I-1
      AP=PRB(I,1)
      AN=PRB(MNA,1)
      IF(AP.GE.X.AND.AN.LE.X) GOTO 25
   10 CONTINUE
C
C   IF THE LOOP HAS BEEN COMPLETED WITHOUT FINDING ANGLES SURROUNDING
C   THE DESIRED ANGLE, THEN AN ERROR FLAG -- IFLAG -- IS SET: IFLAG=1
C
      IFLAG=1
      RETURN
C
C   XB = FRACTIONAL DISTANCE OF THE DESIRED ANGLE BETWEEN THE
C      KNOWN CALIBRATION ANGLES.
C
   25 XB=(X-AN)/(AP-AN)
C
C   THE SEARCH FOR THE PHI VALUES STARTS.  VARIABLES ARE IDENTICAL
C   TO THOSE IN THE PREVIOUS SEARCH EXCEPT 'P' SUBSTITUTES FOR 'A',
C   AND 'Y' AND 'J'  REPLACE 'X' AND 'I' RESPECTIVELY
C
      DO 30 J=2,NP
      MXP=J
      MNP=J-1
      PP=PRB(J,2)
      PN=PRB(MNP,2)
      IF(PP.GE.Y.AND.PN.LE.Y) GOTO 45
   30 CONTINUE
      IFLAG=1
      RETURN
   45 YB=(Y-PN)/(PP-PN)
C
C   WE NOW FIND THE VALUES IN THE CP CALIBRATION TABLE WHICH CORRESPOND
C   TO THE CALIBRATION ANGLES ABOVE AND BELOW THE DESIRED YAW AND PITCH
C
      C11=CP(MNA,MNP)
      C12=CP(MNA,MXP)
      C21=CP(MXA,MNP)
      C22=CP(MXA,MXP)
C
C   Z = THE INTERPOLATED CP VALUE BETWEEN THE FOUR KNOWN CP
C     VALUES: C11, C12, C21, C22
C
      Z=XB*YB*(C22+C11-C12-C21) + XB*(C21-C11) + YB*(C12-C11) +C11
C
C   INTERPOLATION SUCCESSFULLY COMPLETED, ERROR FLAG  IFLAG=0
C
      IFLAG=0
      RETURN
      END
```

APPENDIX II

VELOCITY NOTATION SUMMARY - main program

ALP(I) - Yaw angle of probe setting I

AMIN, AMAX - define the minimum and maximum yaw (alpha) angles of the search grid

COMP - the compressibility factor of the fluid

CP(K) - C_p interpolated from the appropriate calibration table for probe setting K

CPMIN - stores the minimum C_p found during this guess

CPSUM - stores the sum of the four C_p's read by Subroutine CPCAL

CP1, CP2,(I,J) - C_p calibration table for probes 1 and

C0 - sonic velocity

DEL - search grid spacing (degrees of angle)

DENOM - stores an intermediary mathematical quantity

ERRMIN - stores the minimum error found so far for the problem

ERRR - C_p average error characteristic for the guess

GAMMA - ratio of specific heats for the fluid

IER - input error flag = 0 means no error, = 1 an error occurred while reading in the C_p calibrations

IFL - interpolation error flag = 0 interpolation accomplished
= 1 range of the calibration table was insufficient

MACH - fluid Mach number

NALPH1, NALPH2 - number of yaw angles across the edge of the C_{P1}, C_{P2} calibration tables

NPHI1, NPHI2 - number of pitch angles across the edge of the C_{P1}, C_{P2} calibration tables

NPRB(I) - probe type for probe setting I (either 1 or 2)

PHI(I) - pitch angle of probe setting I

PMIN, PMAX - define the minimum and maximum pitch (phi) angles of the search grid.

PRB1, PRB2 (N,J) - contains the alpha and phi angles for use with C_{P1}, C_{P2} respectively. J = 1 refers to yaw angles
J = 2 refers to pitch angles

PRESS(I) - pressure read at setting I

PRMIN - stores the pressure at the setting corresponding to CPMIN

PRSSUM - stores the sum of the four input pressures

PSS - contains a static pressure characteristic for this guess

PTT - contains a total pressure characteristic for this guess

RGAS - ideal gas constant (Joules/kg-°K)

RHO - fluid density

TC - fluid temperature °C

VEL - fluid velocity

WM - molecular weight of the fluid

X,Y - yaw, pitch angle guess (one of the search grid points)

XMIN, YMIN - yaw, pitch angle where the smallest error was found

XR, YR - yaw, pitch angles of the guess relatvve to the probe setting being considered.

NOTATION SUMMARY - SUBROUTINE CPCAL

AP,AN - Yaw angles above and below the desired yaw angle

CP(NA,NP) - C_p calibration table

C11, C12, C21, C22 - C_p values surrounding the desired C_p

IFLAG - error flag = 0 means the interpolation succeeded
1 the range of the C_p table was too small

MNA, MNP - Stores the location of the calibration yaw (alpha), pitch (phi) angles below the desired yaw and pitch angles.

MXA, MXP - Stores the location of the calibration yaw, pitch angles above the desired yaw and pitch angles.

NA, NP - number of yaw, pitch angles in the C_p calibration table

PP, PN - Pitch angles above and below the desired pitch angle

PRB(N,K) - Contains the yaw and pitch angles for the calibration table

X,Y - Yaw and pitch angles where a C_p is sought

XB, YB - Fractional distance of the desired yaw, pitch angle between the known calibration angles

Z - the interpolated C_p value for X, Y

NOTATION SUMMARY - SUBROUTINE INPT

CP(I,J) - Calibration table read from the file

NA - Number of yaw angles on the edge of the C_p table

NP - Number of pitch angles on the edge of the C_p table

PRB(N,K) - contains the yaw and pitch angles for the C_p calibration table
K=1 yaw angles
K=2 pitch angles

APPENDIX III - Sample InpuT

```
 19   19
 -90.00   -80.00   -70.00   -60.00   -50.00   -40.00   -30.00   -20.00   -10.00     0.0
  10.00    20.00    30.00    40.00    50.00    60.00    70.00    80.00    90.00
 -90.00   -80.00   -70.00   -60.00   -50.00   -40.00   -30.00   -20.00   -10.00     0.0
  10.00    20.00    30.00    40.00    50.00    60.00    70.00    80.00    90.00
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00093  0.00350  0.00765  0.01260  0.01735  0.02275  0.02672  0.02930  0.03020  0.02930
0.02672  0.02275  0.01785  0.01260  0.00765  0.00359  0.00093  0.00000  0.00000  0.00369
0.01426  0.03032  0.04977  0.07019  0.08911  0.10435  0.11421  0.11762  0.11421  0.10435
0.08911  0.07019  0.04977  0.03032  0.01426  0.00369  0.00000  0.00000  0.00813  0.03135
0.06640  0.10833  0.15237  0.19265  0.22435  0.24557  0.25271  0.24557  0.22485  0.19265
0.15237  0.10853  0.06640  0.03135  0.00313  0.00000  0.00000  0.01383  0.05321  0.11230
0.18279  0.25552  0.32179  0.37440  0.40808  0.41965  0.40808  0.37440  0.32179  0.25552
0.18279  0.11230  0.05321  0.01383  0.00000  0.00000  0.02008  0.07711  0.16228  0.26325
0.36668  0.46032  0.53423  0.58134  0.59750  0.58134  0.53423  0.46032  0.36668  0.26325
0.16228  0.07711  0.02008  0.00000  0.00000  0.02595  0.09953  0.20307  0.33843  0.47039
0.58934  0.68290  0.74239  0.76277  0.74239  0.68290  0.58934  0.47039  0.33843  0.20307
0.09953  0.02595  0.00000  0.00000  0.03049  0.11690  0.24546  0.39714  0.55171  0.69093
0.80033  0.86985  0.89366  0.86985  0.80033  0.69093  0.55171  0.39714  0.24546  0.11690
0.03049  0.00000  0.00000  0.03303  0.12671  0.26633  0.43142  0.60006  0.75228  0.87215
0.94843  0.97457  0.94843  0.87215  0.75228  0.60006  0.43142  0.26633  0.12671  0.03303
0.00000  0.00000  0.03339  0.12831  0.27027  0.43893  0.61211  0.76923  0.89347  0.97278
1.00000  0.97278  0.89347  0.76923  0.61211  0.43893  0.27027  0.12831  0.03339  0.00000
0.00000  0.03190  0.12280  0.25943  0.42280  0.59174  0.74606  0.86381  0.94750  0.97457
0.94750  0.86381  0.74606  0.59174  0.42280  0.25943  0.12280  0.03190  0.00000  0.00000
0.02856  0.11022  0.23364  0.38232  0.53738  0.68017  0.79454  0.86824  0.89366  0.86824
0.79454  0.68017  0.53738  0.38232  0.23364  0.11022  0.02856  0.00000  0.00000  0.02379
0.09200  0.19570  0.32159  0.45401  0.57699  0.67624  0.74053  0.76277  0.74053  0.67624
0.57699  0.45401  0.32159  0.19570  0.09200  0.02379  0.00000  0.00000  0.01822  0.07061
0.15066  0.24353  0.35629  0.44940  0.52831  0.57968  0.59750  0.57968  0.52831  0.44940
0.35229  0.24353  0.15066  0.07061  0.01822  0.00000  0.00000  0.01257  0.04880  0.10439
0.17271  0.24353  0.31421  0.37027  0.40692  0.41965  0.40692  0.37027  0.31421  0.24558
0.17271  0.10439  0.04880  0.01257  0.00000  0.00000  0.00749  0.02910  0.06234  0.10333
0.14721  0.18869  0.22268  0.24496  0.25271  0.24496  0.22268  0.18869  0.14721  0.10333
0.06234  0.02910  0.00749  0.00000  0.00000  0.00348  0.01351  0.02895  0.04801  0.06843
0.08776  0.10361  0.11400  0.11762  0.11400  0.10361  0.08776  0.06843  0.04801  0.02895
0.01351  0.00343  0.00000  0.00000  0.00090  0.00348  0.00746  0.01237  0.01761  0.02256
0.02662  0.02923  0.03020  0.02928  0.02662  0.02256  0.01761  0.01237  0.00746  0.00348
0.00090  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000
 19   19
 -90.00   -80.00   -70.00   -60.00   -50.00   -40.00   -30.00   -20.00   -10.00     0.0
  10.00    20.00    30.00    40.00    50.00    60.00    70.00    80.00    90.00
 -90.00   -80.00   -70.00   -60.00   -50.00   -40.00   -30.00   -20.00   -10.00     0.0
  10.00    20.00    30.00    40.00    50.00    60.00    70.00    80.00    90.00
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00093  0.00350  0.00765  0.01260  0.01735  0.02275  0.02672  0.02930  0.03020  0.02930
0.02672  0.02275  0.01785  0.01260  0.00765  0.00359  0.00093  0.00000  0.00000  0.00369
0.01426  0.03032  0.04977  0.07019  0.08911  0.10435  0.11421  0.11762  0.11421  0.10435
0.08911  0.07019  0.04977  0.03032  0.01426  0.00369  0.00000  0.00000  0.00813  0.03135
0.06640  0.10833  0.15237  0.19265  0.22435  0.24557  0.25271  0.24557  0.22485  0.19265
0.15237  0.10853  0.06640  0.03135  0.00313  0.00000  0.00000  0.01383  0.05321  0.11230
0.18279  0.25552  0.32179  0.37440  0.40808  0.41965  0.40808  0.37440  0.32179  0.25552
0.18279  0.11230  0.05321  0.01383  0.00000  0.00000  0.02008  0.07711  0.16228  0.26325
0.36668  0.46032  0.53423  0.58134  0.59750  0.58134  0.53423  0.46032  0.36668  0.26325
0.16228  0.07711  0.02008  0.00000  0.00000  0.02595  0.09953  0.20307  0.33843  0.47039
0.58934  0.68290  0.74239  0.76277  0.74239  0.68290  0.58934  0.47039  0.33843  0.20307
0.09953  0.02595  0.00000  0.00000  0.03049  0.11690  0.24546  0.39714  0.55171  0.69093
0.80033  0.86985  0.89366  0.86985  0.80033  0.69093  0.55171  0.39714  0.24546  0.11690
0.03049  0.00000  0.00000  0.03303  0.12671  0.26633  0.43142  0.60006  0.75228  0.87215
0.94843  0.97457  0.94843  0.87215  0.75228  0.60006  0.43142  0.26633  0.12671  0.03303
0.00000  0.00000  0.03339  0.12831  0.27027  0.43893  0.61211  0.76923  0.89347  0.97278
1.00000  0.97278  0.89347  0.76923  0.61211  0.43893  0.27027  0.12831  0.03339  0.00000
0.00000  0.03190  0.12280  0.25943  0.42280  0.59174  0.74606  0.86381  0.94750  0.97457
0.94750  0.86381  0.74606  0.59174  0.42280  0.25943  0.12280  0.03190  0.00000  0.00000
0.02856  0.11022  0.23364  0.38232  0.53738  0.68017  0.79454  0.86824  0.89366  0.86824
0.79454  0.68017  0.53738  0.38232  0.23364  0.11022  0.02856  0.00000  0.00000  0.02379
0.09200  0.19570  0.32159  0.45401  0.57699  0.67624  0.74053  0.76277  0.74053  0.67624
0.57699  0.45401  0.32159  0.19570  0.09200  0.02379  0.00000  0.00000  0.01822  0.07061
0.15066  0.24353  0.35629  0.44940  0.52831  0.57968  0.59750  0.57968  0.52831  0.44940
0.35229  0.24353  0.15066  0.07061  0.01822  0.00000  0.00000  0.01257  0.04880  0.10439
0.17271  0.24353  0.31421  0.37027  0.40692  0.41965  0.40692  0.37027  0.31421  0.24558
0.17271  0.10439  0.04880  0.01257  0.00000  0.00000  0.00749  0.02910  0.06234  0.10333
0.14721  0.18869  0.22268  0.24496  0.25271  0.24496  0.22268  0.18869  0.14721  0.10333
0.06234  0.02910  0.00749  0.00000  0.00000  0.00348  0.01351  0.02895  0.04801  0.06843
0.08776  0.10361  0.11400  0.11762  0.11400  0.10361  0.08776  0.06843  0.04801  0.02895
0.01351  0.00343  0.00000  0.00000  0.00090  0.00348  0.00746  0.01237  0.01761  0.02256
0.02662  0.02923  0.03020  0.02928  0.02662  0.02256  0.01761  0.01237  0.00746  0.00348
0.00090  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
0.00000
```

SAMPLE INPUT (Con't)

```
28.80             1.40         20.0         1.0
107660           -25.0         0.           1
105890.           0.           0.           1
102550.           25.0         0.           1
107580.           0.           25.0         2
109140.
109740.
107090.
108900.
102820.
109170.
109190.
105980.
 98100.
105450.
108120.
 99180.
120000.          0.           0.           1
115090.          0.           25.0         2
115010.          -25.0        0.           1
115010.          25.0         0.           1
112940.
110640.
116650.
111370.
```

APPENDIX IV – Sample Output

```
FLUID PROPERTIES :

MOLECULAR WT =                       28.8000
RATIO OF SPECIFIC HEATS =             1.4000
TEMPERATURE DEG C =                  10.0000
COMPRESSIBILITY FACTOR =              1.0000


PROBE        YAW         PITCH          PRESSURE
 TYPE      SETTING      SETTING        READ  (PA)

  1        -25.00         0.0          107660.00
  1          0.0          0.0          105990.00
  1         25.00         0.0          102550.00
  2          0.0         25.00         107580.00


  1        -25.00         0.0          109140.00
  1          0.0          0.0          109740.00
  1         25.00         0.0          107090.00
  2          0.0         25.00         108900.00


  1        -25.00         0.0          102920.00
  1          0.0          0.0          109190.00
  1         25.00         0.0          109190.00
  2          0.0         25.00         105980.00


  1        -25.00         0.0           98100.00
  1          0.0          0.0          105450.00
  1         25.00         0.0          103120.00
  2          0.0         25.00          99180.00


  1          0.0          0.0          120000.00
  2          0.0         25.00         119090.00
  1        -25.00         0.0          115010.00
  1         25.00         0.0          115010.00


  1          0.0          0.0          118840.00
  2          0.0         25.00         110640.00
  1        -25.00         0.0          116650.00
  1         25.00         0.0          111370.00

    STATIC         TOTAL                  YAW       PITCH         VELOCITY    MACH
 PRESS (PA)     PRESS (PA)               ANGLE      ANGLE         (M/SEC)    NUMBER


  100038.98     110152.75               -30.37      30.37          128.76     0.374
  100069.56     110096.19                -8.15       5.56          128.00     0.372
   90019.19     110127.56                12.59       0.77          187.42     0.544
   89898.63     110130.23                23.15     -18.52          188.03     0.546
   91004.19     119988.75                -0.00      -0.00          220.67     0.641
   89879.94     120135.38                -7.04      -9.63          226.28     0.657
```

APPENDIX V

NOTES ON THE USE OF VELOCITY

INPUT: The required input consists of probe calibration data, fluid properties, and finally the experimental pressures. Subroutine INPUT reads the calibration data from each probe type in the following form:

1. The first card contains the number of yaw and pitch angles on the axes of the calibration table (format 2I4)

   Ex: 19 19 means 19 yaw and 19 pitch angles were used in the calibration and the C_p table will therefore be 19 x 19 in size.

2. The next few cards contain the values of the yaw angles where calibration points were taken in the C_p table. Values are entered in format F8.2, one angle every 8 columns. After all the yaw angles have been read, the pitch angles are entered starting on a new card.

3. The experimentally determined C_p's of the calibration surface can now be read for each angle pair starting from the smallest yaw and pitch angle and with the pitch angle varying most rapidly. Ex.

   C_p(-90), -90), C_p(-90, -80)... C_p's are read format F 8.5.

All of the calibration data are read on Machine Unit 8: Cards are assumed to be 80 characters in length.

The following fluid properties are entered next:

Molecular Weight

Ratio of Specific Heats

Fluid Temperature Deg C

Compressibility Factor

Machine Unit 6 reads this data from one card, Format 4 F10A.

At last the experimental results are entered. Four cards are required for each trial, one card per setting. For format:

Columns 1-10: Experimental pressure
11-20: Yaw Angle
21-30: Pitch Angle
31: Probe Type (1,2, or blank)

If Column 31 is left blank, only the experimentally read pressure is registered; yaw and pitch angles for that setting remain unchanged from the previous trial. The first trial must contain angle settings and probe type since no default values have been assumed. Again machine unit 6 is used to read this data. When no more experimental pressure data is available, the program terminates.

The experimental pressures can be based in any absolute system of measurement; ex.: Psia, KPa, Atm, mmHg, with the same numerical results (the units in the titles of the static and total pressure columns will not apply). The analysis below shows that in determining velocity, the pressure units cancel.

The velocity is calculated from $V = MC_o$, where, from Eq. (1),

$$M = \left[\frac{(P_T/P_S)^{\frac{\gamma-1}{\gamma}} - 1}{(\gamma-1)/2} \right]^{1/2}$$

and $$C_o = \sqrt{\gamma RT}$$

Here,

C_o = sonic velocity

M = Mach number

P_S, P_T = fluid static, total pressure

R = ideal gas constant

$= \frac{8314 \text{ Joules/kg mole}^{\circ}\text{K}}{\text{MW}}$

T = Fluid Temperature $^{\circ}$K

V = Fluid Velocity (m/sec)

ρ = Fluid density

γ = ratio of specific heats

CPCAL: A linear, double-interpolation scheme is employed to determine a value of C_p between four points. A second-order, double-interpolation scheme has also been devised and tested, and is presented at the end of this report. Figure V-1 is a graph of the accuracy of both schemes as a function of the number of calibration points in the C_p table. Values were determined by filling a calibration table, extending from -90° to $+ 90^{\circ}$ in yaw and pitch with the C_p's which would result from an ideal probe, and testing 6084 points (78 x 78) within the table. If no highly unusual distortions in the calibrations of the probes occurs, Figure V-1 shows that a significant reduction in the amount of calibration required is possible with a second order scheme. Further, if the accuracy of the C_p determinations is known, Figure V-1 can provide an estimate of the number of points needed.

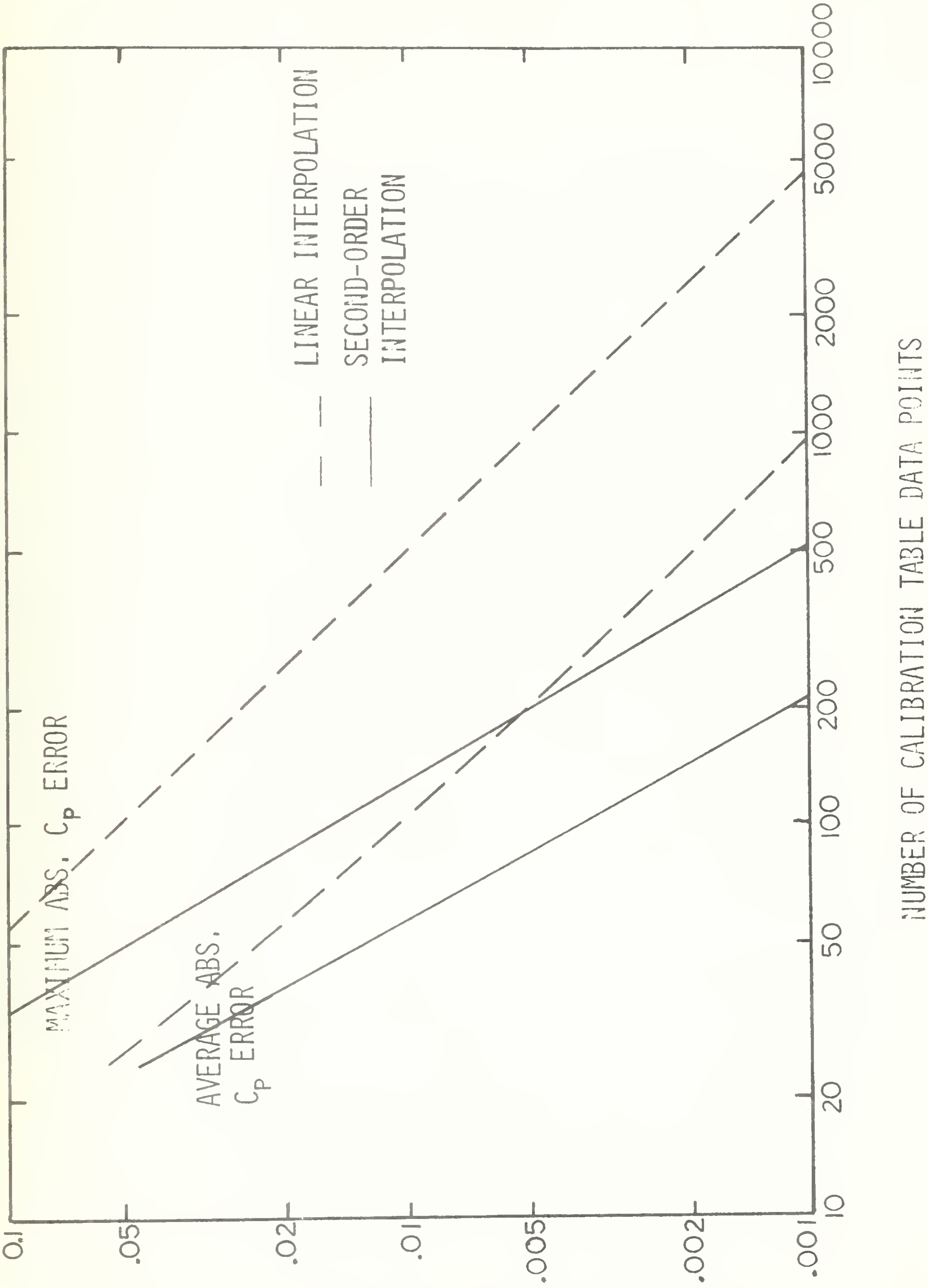

Figure V-1 C_p Error vs. Number of Data Points

Second-Order Double-Interpolation Scheme

```
C
C
C
      SUBROUTINE CPCAL(NA,NP,PRB,CP,X,Y,Z,IFLAG)
C        NA,NP = # OF ALPHA AND PHI ANGLES IN THE CP CALIBRATION
C        A(NA) = VALUES OF THE ALPHAS IN THE CALIBRATION TABLE (YAW ANGL
C        P(NP) = VALUES OF THE PHIS IN THE CALIBRATION TABLE (PITCH ANGL
C        CP(NA,NP) = VALUE OF CP FOR EACH ANGLE SET ( A(NA),P(NP) )
C        X       = DESIRED ALPHA ANGLE
C        Y       = DESIRED PHI ANGLE
C        Z       = CALCULATED CP
C        IFLAG = ERROR FLAG
C        THIS PROGRAM ESTIMATES THE VALUE OF CP FOR A GIVEN ANGULAR INPU
C     ALPHA, PHI, USING A LINEAR DOUBLE INTERPOLATION SCHEME BETWEEN KNO
C     VALUES OF CP FOR ANGLES ABOVE AND BELOW THE DESIRED ANGLE.
      DIMENSION PRB(NA,2) ,CP(NA,NP)
      DO 10 I=2,NA
 20   MXA=I
      MNA=I-1
      MMA=MXA+1
      IF(MMA.GT.NA) MMA=MNA-1
      AP=PRB(I,1)
      AN=PRB(MNA,1)
      AQ=PRB(MMA,1)
      IF(AP.GE.X.AND.AN.LE.X) GOTO 25
 10   CONTINUE
      IFLAG=1
      RETURN
 25   DO 30 J=2,NP
 40   MXP=J
      MNP=J-1
      MMP=MXP+1
      IF(MMP.GT.NP) MMP=MNP-1
      PP=PRB(J,2)
      PN=PRB(MNP,2)
      PQ=PRB(MMP,2)
      IF(PP.GE.Y.AND.PN.LE.Y) GOTO 45
 30   CONTINUE
      IFLAG=1
      RETURN
 45   C11=CP(MNA,MNP)
      C12=CP(MNA,MXP)
      C13=CP(MNA,MMP)
      C21=CP(MXA,MNP)
      C22=CP(MXA,MXP)
      C23=CP(MXA,MMP)
      C31=CP(MMA,MNP)
      C32=CP(MMA,MXP)
      C33=CP(MMA,MMP)
      F1=(X-AP)*(X-AQ)/(AN-AP)/(AN-AQ)
      F2=(X-AN)*(X-AQ)/(AP-AN)/(AP-AQ)
      F3=(X-AN)*(X-AP)/(AQ-AN)/(AQ-AP)
      C1=F1*C11+F2*C21+F3*C31
      C2=F1*C12+F2*C22+F3*C32
      C3=F1*C13+F2*C23+F3*C33
      Z=(Y-PP)*(Y-PQ)/(PN-PP)/(PN-PQ)*C1 +
    1   (Y-PN)*(Y-PQ)/(PP-PN)/(PP-PQ)*C2 +
    2   (Y-PN)*(Y-PP)/(PQ-PN)/(PQ-PP)*C3
      RETURN
      END
```

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