TECHNICAL NOTE

# LOOK UP TABLE METHOD FOR FIVE HOLE PROBE DATA REDUCTION

N. Sitaram, M. Suresh, Satyansh Kumar, P.M. Dileep Chandran, B.V.S.S.S. Prasad
Thermal Turbomachines Laboratory
Department of Mechanical Engineering
Indian Institute of Technology Madras
Chennai-600 036, India
Email : nsitaram.iitm@gmail.com

**Abstract**

*A lookup method for extracting flow field information from five hole probe measurements is presented. The look up table method consists of two step interpolation. In the first step, the calibration space is divided into a large number of small intervals of yaw and pitch coefficients (0.1, 0.05 or 0.01) and the required quantities are interpolated using local cubic spline interpolation technique. The interpolated values are stored in a large square matrix. In the second step, the measured values of yaw and pitch coefficients are used to determine yaw and pitch angles by linear interpolation. Same procedure is used to determine total and static pressure coefficients. Additional data taken during the calibration is used for validating lookup table method and spline interpolation method. The errors from the look up table method, particularly with the interval of 0.01 are about the same or lower than those obtained from the spline interpolation method. The computational times for lookup table method are found to be lower than that for the spline interpolation method. The lookup table method seems to be attractive when a large amount of five hole probe data is to be processed and in cases where online data processing is required.*

***Keywords**: Five Hole Probe, Non-nulling Calibration, Lookup Table Method, Spline Interpolation Method, Interpolation Errors*

## Nomenclature

$C_{PPITCH}$ = Pitch coefficient (Defined in the text)
$C_{PS}$ = Static pressure coefficient (Defined in the text)
$C_{PYAW}$ = Yaw coefficient (Defined in the text)
$C_{PO}$ = Total pressure coefficient (Defined in the text)
D = Probe dynamic head (Pa) (Defined in the text)
PM = Mean pressure (Pa)
$P_O$ = Total pressure (Pa)
$P_S$ = Static pressure (Pa)
$\alpha$ = Yaw angle (deg)
$\beta$ = Pitch angle (deg)
$\Delta$ = Error in interpolated value

### Subscripts

ABS = Average value of absolute error
MAX = Maximum value of error
MIN = Minimum values of error

## Introduction

Five hole probes are extensively used to measure three-dimensional flows in many aerodynamic and turbomachinery flows [1]. The probes are available in different tip shapes [2]. A thermocouple added to the probe head makes it suitable for compressible flow measurements. A probe with fast response pressure transducers directly attached to the probe head or embedded in the tubes can be used to measure periodical flows behind the turbomachinery rotors. The pressures measured by the five holes can be used to determine the four unknowns, namely total and static pressures and flow and spanwise angles. Either a polynomial curve fit or local spline interpolation is used to determine these unknowns. Once the four unknowns are determined, velocity and its three components can be calculated.

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However polynomial fit or spline interpolation is cumbersome, as they involve two independent variables. This problem is serious if large amount of data is to be processed or real time data reduction is required for periodic flow measurements. Hence the present investigation is undertaken to develop a computationally less intensive method to process data from five hole probes, namely lookup table method. Similar methods are developed by Lueptow et al. [3] for a two sensor hot wire probe, Maciel and Gleyzes [4] for a four sensor hot wire probe and Wenger and Devenport [5] for a seven hole probe.

### Objective

The objective of the present paper is to develop a look up table method for processing the pressure data obtained from a five hole probe to determine the four unknowns, namely total and static pressures and flow angles in mutually perpendicular directions in an unknown three-dimensional incompressible flow. Look up table method is developed with different intervals. Additional data taken during the calibration of the five hole probe are used for validating the look up table method and the spline interpolated method and compared with the interpolated values for accuracy. In addition the computer time required for both the methods are compared.

### Calibration Details

A five hole probe of 3 mm tip diameter is calibrated in an open jet calibration tunnel with the calibration nozzle diameter of 100 mm at a velocity of 50 m/s. The details of calibration tunnel and its accessories along with the calibration procedure are presented in Jangir et al. [6] and the reader is referred to this paper for the calibration details. The probe is calibrated in the yaw and pitch angle range of ±30° at an interval of 5°. Additional data taken are at all the pitch intervals at two values of yaw, i.e. at -7.5 and 22.5 deg. These data are used for validating the lookup table method and spline interpolation method.

Calibration data are given in terms of five pressures, viz. central ($P_C$), left ($P_L$), right ($P_R$), top ($P_T$) and bottom ($P_B$) hole pressures for each pair of $\alpha$ and $\beta$. They are non-dimensionalized by dividing them with the settling chamber pressure. The calibration coefficients $C_{PYAW}$, $C_{PPITCH}$, $C_{PO}$ and $C_{PS}$ are calculated from the non-dimensionalized pressures as per the definitions given below:

$$PM = (P_L + P_R + P_T + P_B)/4$$

$$D = P_C - PM$$

$$C_{PYAW} = (P_L - P_R)/D$$

$$C_{PPITCH} = (P_T - P_B)/D$$

$$C_{PO} = (P_O - P_C)/D$$

$$C_{PS} = (PM - P_S)/D$$

The calibration coefficients are presented in Fig.1 as follows:

$C_{PPITCH}$ vs. $C_{PYAW}$ for various values of yaw and pitch angles, $\alpha$ and $\beta$ and

Contours of $C_{PO}$ and $C_{PS}$ with yaw angle, $\alpha$ and pitch angle, $\beta$ on the X and Y axes.

Grid lines in the $C_{PPITCH}$ vs. $C_{PYAW}$ calibration curves are also shown. For the sake of clarity, only representative grid lines are shown. These grid lines are necessary for developing the look up table method.

### Development of Lookup Table Method

The aim is to generate lookup tables for $\alpha$, $\beta$, $C_{PO}$ and $C_{PS}$ as a function of $C_{PYAW}$ and $C_{PPITCH}$ from the given calibration data. The procedure is divided into following three parts:

- Input/ Output operation.
- Interpolation for $\alpha$ and $\beta$.
- Interpolation for $C_{PO}$ and $C_{PS}$.

**Input/ Output Operations**: Input/ Output and calling of interpolation functions are done in the main function of the program. Calibration data for $C_{PYAW}$, $C_{PPITCH}$, $C_{PO}$ and $C_{PS}$ are read from excel file and stored in different 2-D arrays. Input of interpolation interval is taken.

**Interpolation for $\alpha$ and $\beta$**: Data of yaw and pitch coefficients, $C_{PYAW}$ and $C_{PPITCH}$ are given as a function of $\alpha$ and $\beta$. It is required to generate lookup tables for $\alpha$ and $\beta$ at the specified intervals of $C_{PYAW}$ and $C_{PPITCH}$. Piecewise cubic local spline curve is used to form the curve passing through given data points, then values at interpolated points are determined at the desired intervals. This is done using spline interpolation method described below. Same procedure is used for generating lookup tables for both yaw and pitch angles.

**Interpolation for $C_{PO}$ and $C_{PS}$**: Data of total and static pressure coefficients, $C_{PO}$ and $C_{PS}$ are given as function of α and β but it is required to generate lookup table for them at the specified intervals of $C_{PYAW}$ and $C_{PPITCH}$. This is achieved by using lookup tables for yaw and pitch angles which are generated in the last step. Again piecewise cubic local spline curve is used to form the curve passing through given data points, and then values at interpolated points are determined at the desired intervals.

### Validation of Lookup Table Method

Validation is done by searching and locating input values of $C_{PYAW}$ and $C_{PPITCH}$ in the four lookup tables of α, β, $C_{PO}$ and $C_{PS}$. The value may not be exactly present in lookup tables so a grid of four points in which input value lies is located. The values corresponding to these grid points are two dimensionally linearly interpolated to get the desired values of α, β, $C_{PO}$ and $C_{PS}$ in respective lookup tables.

### Spline Interpolation Method

In this method calibration space is directly interpolated to get the required quantity. For every input value of $C_{PYAW}$ and $C_{PPITCH}$, separate interpolation is done to determine different parameters. Piecewise cubic local spline curve is used to form the curve passing through given data points, and then values at the interpolated points are determined at the desired point. Calibration data and validation data are stored in 2-D arrays. This technique is well established and used by many investigators for processing measured data from five hole probes, Treaster and Yocum [1] and from seven hole probes, Venkateswara Babu et al. [7].

## Results and Discussion

### Lookup Tables

Data from the lookup tables for α, β, $C_{PO}$ and $C_{PS}$ are presented as contours with $C_{PYAW}$ and $C_{PPITCH}$ on the X and Y axes respectively in Figs.2 to 5 respectively. Contours of constant yaw angles are nearly vertical in the region near zero yaw angle, while contours of constant pitch angles are nearly horizontal in the region near zero pitch angle. In all the figures, interpolated data in the centre region follows the trends similar to the calibration data. In the zonal boundary region there is some divergence from the calibration data. This is due to extrapolation in that region. For both look up table and spline interpolation methods, the first step is to check if the values of yaw and pitch coefficients calculated from the measured pressure data fall inside the calibration space of the $C_{PPITCH}$ vs. $C_{PYAW}$ calibration space. If any of these values fall outside the calibration space, the corresponding data is rejected.

### Validation of Lookup Table Method

Lookup table method is validated by using additional data taken during the calibration data as the input to the look up table method. Validation is done for the three interval values 0.1, 0.05 and 0.01 for which look up table data are available. The interpolated results from the lookup tables for the three intervals are compared along with the values obtained from the spline interpolation method. Minimum and maximum values of the errors and average of absolute errors in yaw and pitch angles and total and static pressure coefficients are given in Tables-1 to 4 respectively. From the tables it is clear that the errors for the lookup tables with intervals of 0.1 and 0.05 are nearly equal and slightly higher than those for the lookup tables with intervals of 0.01. However the errors are still lower than obtained from the spline interpolation method.

### Requirements of Computational Time

The computational times required for generating lookup tables and required for data reduction are given in Table-5 along with the time required for data reduction for the spline interpolation method. The time required for data reduction is for 10 times the validation data as the validation data is given 10 times as input data to both the methods. From the table, it is clear that the time required for generating lookup table increases with the reduction in the interval. However the time required for data reduction remains nearly constant with the interval and is about 7 times lower than that required for the spline interpolation method. Although the total time (time required for generating lookup table and time required for data reduction) is more for the look up table method with an interval of 0.01, it has to be understood the time required for generating lookup table is one time requirement. Hence the look up table with a small interval is preferable when a large amount of five hole probe data is to be interpolated and in the case of real time data reduction required for periodic data acquisition using a five hole probe with fast response pressure transducers.

Although the look up table method is developed for use with a five hole probe with the calibration done at equal ranges in both yaw and pitch planes, the method is

**Table-1 : Error Table of Yaw Angle**

| | | $\Delta\alpha_{MIN}$ | $\Delta\alpha_{MAX}$ | $\Delta\alpha_{ABS}$ |
|---|---|---|---|---|
| Lookup Table Method | Interval: 0.10 | -0.36 | 0.98 | 0.31 |
| | Interval: 0.05 | -0.41 | 0.97 | 0.33 |
| | Interval: 0.01 | -0.41 | 0.97 | 0.33 |
| Spline Interpolation Method | | -1.24 | 1.09 | 0.44 |

**Table-2 : Error Table of Pitch Angle**

| | | $\Delta\beta_{MIN}$ | $\Delta\beta_{MAX}$ | $\Delta\beta_{ABS}$ |
|---|---|---|---|---|
| Lookup Table Method | Interval: 0.10 | -0.71 | 0.61 | 0.28 |
| | Interval: 0.05 | -0.70 | 0.61 | 0.28 |
| | Interval: 0.01 | -0.70 | 0.61 | 0.28 |
| Spline Interpolation Method | | -0.65 | 0.80 | 0.29 |

**Table-3 : Error Table of $C_{PO}$**

| | | $\Delta C_{POMIN}$ | $\Delta C_{POMAX}$ | $\Delta C_{POABS}$ |
|---|---|---|---|---|
| Lookup Table Method | Interval: 0.10 | -0.025 | 0.015 | 0.006 |
| | Interval: 0.05 | -0.027 | 0.015 | 0.006 |
| | Interval: 0.01 | -0.014 | 0.015 | 0.005 |
| Spline Interpolation Method | | -0.050 | 0.028 | 0.013 |

**Table-4 : Error Table of $C_{PS}$**

| | | $\Delta C_{PSMIN}$ | $\Delta C_{PSMAX}$ | $\Delta C_{PSABS}$ |
|---|---|---|---|---|
| Lookup Table Method | Interval: 0.10 | -0.006 | 0.002 | 0.002 |
| | Interval: 0.05 | -0.006 | 0.002 | 0.002 |
| | Interval: 0.01 | -0.006 | 0.001 | 0.002 |
| Spline Interpolation Method | | -0.004 | 0.010 | 0.003 |

**Table-5 : Computational Time for Interpolation Methods**

| | | Time Required for Generating Lookup Table (sec) | Time Required for Data Reduction (sec) | Total Time |
|---|---|---|---|---|
| Lookup Table Method | Interval: 0.10 | 0.85 | 2.08 | 2.93 |
| | Interval: 0.05 | 1.89 | 2.11 | 4.0 |
| | Interval: 0.01 | 16.76 | 1.95 | 18.71 |
| Spline Interpolation Method | | Nil | 13.39 | 13.39 |

successfully applied for data reduction of a four hole probe with the calibration done at unequal ranges in yaw and pitch planes [8] and an ultra miniature three dimensional wake probe [9].

### Conclusions

The following conclusions are drawn from the present investigation.

- The look up table method is as accurate or more accurate than the conventional direct interpolation method and also computationally less intensive.
- The look up table method seems to be attractive when large amount of five hole probe data are to be processed. This method can also be used with four hole probes also.
- This method is also attractive when real time data reduction is required from fast response five hole probe. From the processed data, the measurement positions can be conveniently adapted in real time.

### References

1. Treaster, A. L. and Yocum, A. M., "The Calibration and Application of Five-hole Probes", Instrumentation Society of America Transactions, Vol.18, No.3, pp.23-34.

2. Yasa, T. and Paniagua, G., "Robust Procedure for Multi-hole Probe Data Processing", Flow Measurement and Instrumentation 26, 2012, pp.46-54.

3. Lueptow, R. M., Breuer, K. S. and Haritonidis, J. H., "Computer-aided Calibration of X-probes Using a Look-up Table", Experiments in Fluids, Vol.6, 1988, pp.115-118.

4. Maciel, Y. and Gleyzes, C., "Survey of Multi-wire Probe Data Processing Techniques and Efficient Processing of Four-wire Probe Velocity Measurements in Turbulent Flows", Experiments in Fluids, Vol.29, 2000, pp. 66-78.

5. Wenger, C. W. and Devenport, W. J., "Seven-Hole Pressure Probe Calibration Method Utilizing Look-Up Error Tables", AIAA Journal, Vol.37, No.6, 1999, pp.675-680.

6. Jangir Ravirai., Sitaram, N. and Gajanan, Ct., "A Miniature Four-hole Probe for Measurement of Three-Dimensional Flow with Large Gradients", International Journal of Rotating Machinery, Vol.2014, Article ID297861, 12 pages, http://dx.doi.org/10.1155/2014/297861.

7. Venkateswara Babu, C., Govardhan, M. and Sitaram, N., "A Method of Calibration of Seven Hole Pressure Probe for Measuring Highly Three Dimensional Flows", Measurement Science and Technology, Vol.9, No.3, pp.468-476.

8. Suresh, M. and Sitaram, N., "Extended Calibration of a Four Hole Probe for Three Dimensional Flow Measurements", International Journal of Rotating Machinery, Vol.2016, Article ID 5327297, 2016, 12 Pages.

9. Gajanan and Sitaram, N., "Sub Miniature Four Hole Probe for Three Dimensional Wake Measurements", Proceedings of the IEEE National Conference on Recent Advances in Mechanical Engineering (RAME-2014), February 7, 2014, pp.31-40, Chennai, Tamil Nadu.

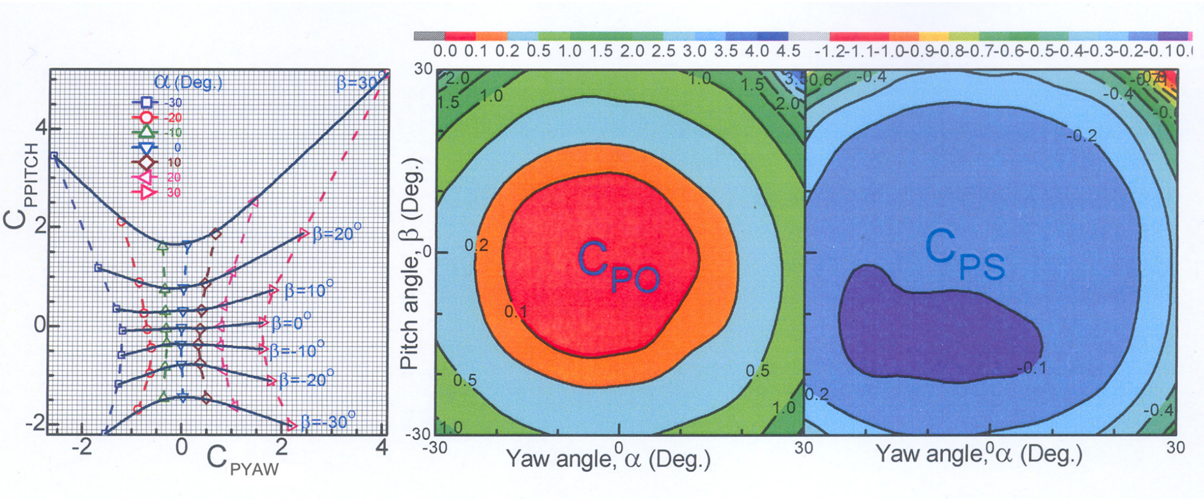


Fig.1 Calibration Curves of the Five Hole Probe

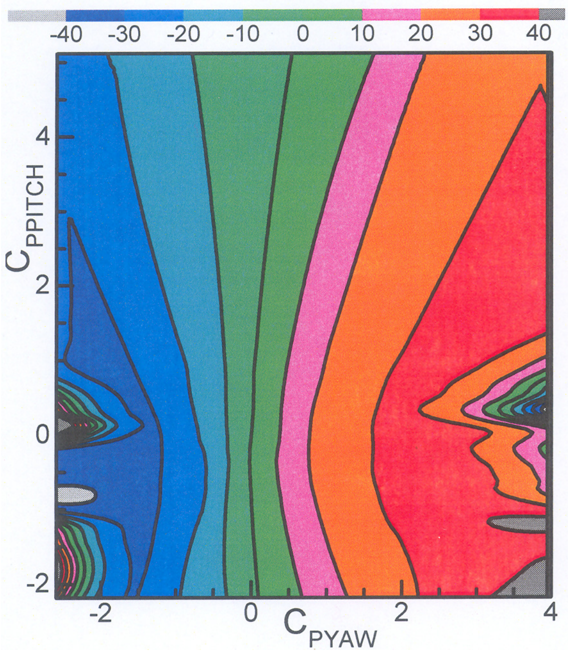


Fig.2 Interpolated Results for Yaw Angle : Lookup Table Method (Interval:0.01)

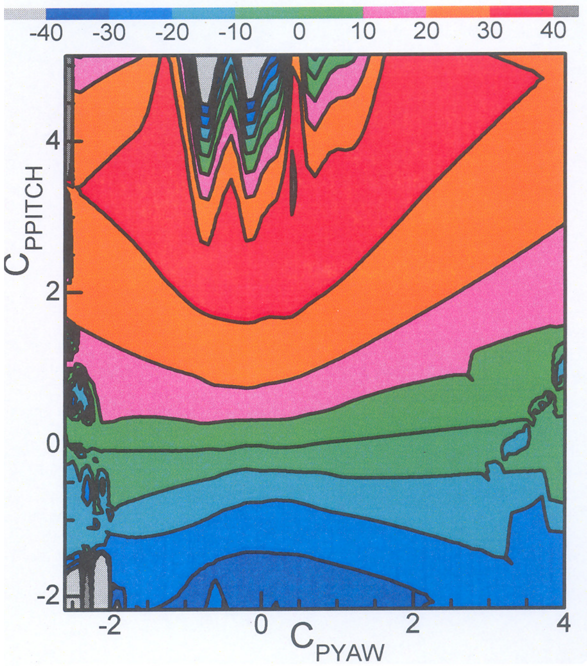


Fig.3 Interpolated Results for Pitch Angle : Lookup Table Method (Interval:0.05)

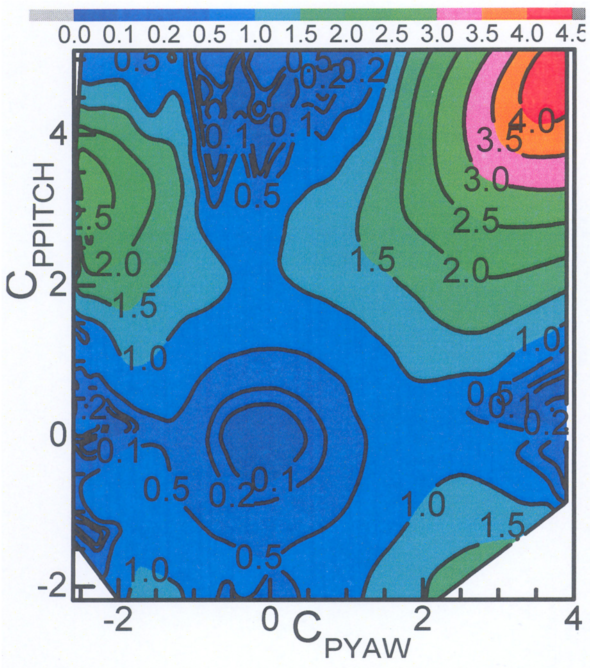


*Fig.4 Interpolated Results for $C_{PO}$: Lookup Table Method (Interval: 0.1)*

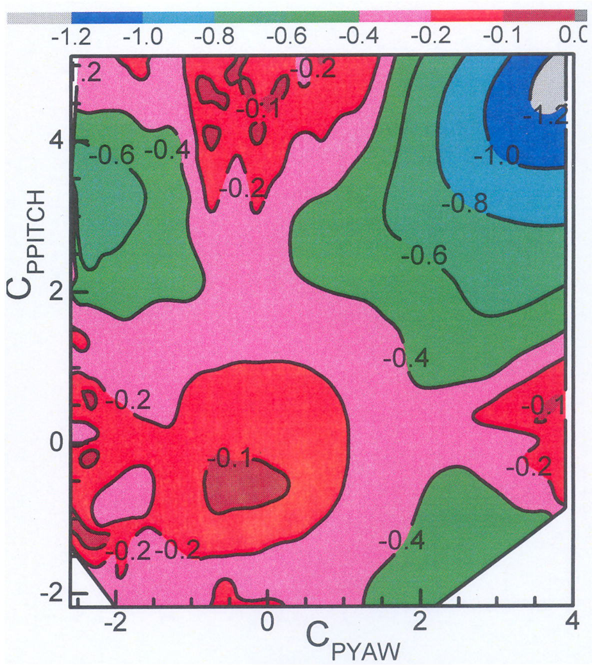


*Fig.5 Interpolated Results for $C_{PS}$: Lookup Table Method (Interval: 0.1)*