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CALIBARTION OF A FOUR - HOLE PYRAMID PROBE FOR LOSS MEASUREMENT IN A TRANSONIC CASCADE TUNNEL

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Abstract

A four-hole pyramid probe has been calibrated for use in an annular, transonic turbine cascade tunnel. It will be used to measure total pressure, Mach number and two flow angles. The probe was calibrated in an ejector-driven, perforated-wall transonic tunnel over the Mach number range 0.5 to 1.2, with pitch angles from -20^o to $+20^o$ and yaw angles from -23.6^o to $+23.6^o$. A computer-driven automatic traversing mechanism and data collection system were used to acquire a large *probe calibration matrix* of flow variables and non-dimensional calibration coefficients. A novel method was used to transform this matrix into a *probe application matrix* of flow variables at fixed values of the calibration coefficients. This then acts as a look-up table which means that interpolation is only required within one cuboid-shaped cell. Such a method is considerably more efficient than a simple global searching routine.

1 Nomenclature

1.1 Symbols

C_{ax}	Axial chord
C_α	Pitch coefficient
C_β	Yaw coefficient
C_M	Mach number coefficient
C_t	Total pressure coefficient
D	Pressure Difference ($P_A - P_{av}$)
M	Mach number
P	Pressure
Re	Reynolds Number
α	Pitch angle
β	Yaw angle
γ	Ratio of specific heats

1.2 Subscripts

0	Stagnation conditions
A, B, C, D	Holes of the probe (see figure 1)
av	Average value

2 Introduction

Multi-hole pressure probes have long been used in turbomachinery applications. Measurements of flow angles and Mach number with such probes are necessary for determining losses in linear and annular cascades and are currently being widely used to provide data for the validation of computational predictions.

Traditionally, five-hole probes, with four equi-spaced side holes around a central hole, have been used for aerodynamic measurements in three-dimensional flowfields (Dominy and Hodson 1992). The use of five pressure holes for three-dimensional probes accumulates redundant information as the probe need only have the minimum number of holes to measure the relevant flowfield variables (say, total pressure, Mach number and two flow angles), which is four. Hence four-hole probes have become more common in recent years (Shepherd 1981, Sitaram and Treaster 1985, Hooper and Musgrove 1991, Cherrett, Bryce and Hodson 1992), having the advantage of smaller size, fewer measurements in calibration and application, and less instrumentation.

In continuous wind tunnels multi-hole probes are usually used in nulled mode, with the probe angled to face directly into the incoming flow. This has the advantage of not requiring accurate pitch and yaw calibration. However, in short-duration tunnels and in turbomachines with spatial restrictions, the nulling process is impractical and a three-dimensional calibration is therefore necessary. The probe described in this paper was developed specifically for use in such a short-duration tunnel, namely the Oxford University transonic annular blowdown cascade tunnel.

There is very little in the literature about how to transform the calibration data into a usable form for converting experimental data into flowfield measurements, especially in the case when Mach number variations are also being taken into account. Methods using polynomial surfaces as approximations (Koschel and Pretzsch 1988, Kupferschmied and Gossweiler 1992) require a lot of computing power for a small degree in the polynomials and can produce large errors. This paper proposes a novel method for tackling this problem, which copes remarkably well with the large degree of non-linearity of the calibration coefficients in the transonic regime.

3 Probe Geometry

The probe is shown in figure 1. The probe is a four-hole, truncated pyramid probe, similar to that used in

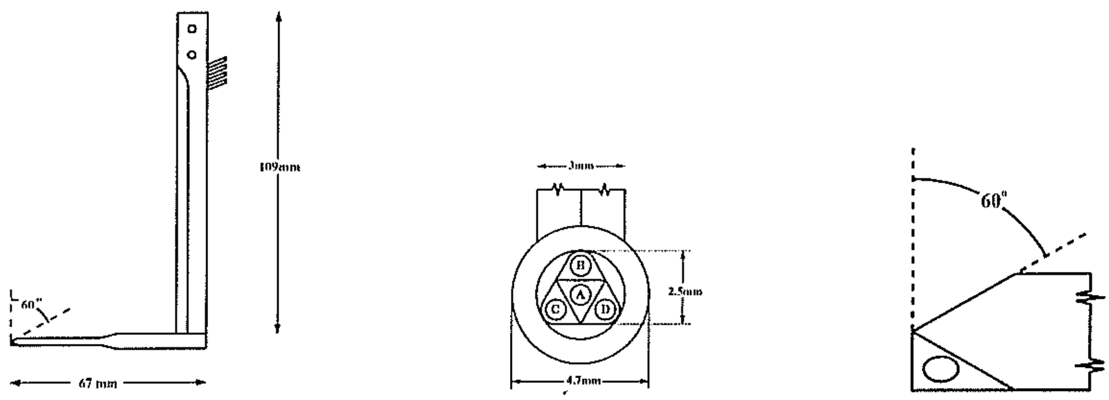


Figure 1: *The Probe.* Left: *Side view;* Centre: *Hole labelling convention and dimensions of the probe tip;* Right: *Angle of the probe face*

incompressible flow by Shepherd (1981), but with side faces inclined at 60° to the normal to the probe sting to improve transonic performance. The 67 mm long, slender sting is aligned with the mean flow. The stem used was designed for better aerodynamic performance than the commonly used cylindrical shape and to prevent its bow shock from interacting with the probe tip.

An important consideration in the design was the desire to create a compact probe which produced minimum blockage and no redundant data; the other main consideration was to make the probe as insensitive to Reynolds number as possible, since the correct probe Reynolds number could not be produced in the calibration tunnel. The use of the sharp-edged, faceted probe tip with well-defined separation lines ensures that the probe is less Reynolds number sensitive than the more frequently used conical and spherical probes. These factors are similar to those that guided Cherrett et al. (1992) to decide upon a similar probe following experiments by Dominy and Hodson (1992) on five-hole probes.

The probe was constructed from four stainless steel hypodermic tubes of 1.0 mm outer diameter and three solid stainless steel rods of the same outer diameter. These were placed into a 4.7 mm outer diameter, 3.1 mm inner diameter stainless steel tube, with one hypodermic tube in the centre and the remaining hypodermic tubes alternating with the solid rods. This confined the hypodermic tubes to being in the correct positions relative to each other. The gaps were then filled with hard solder and the triangular length of sting and the four faceted faces were machined from this. The outer tube was then welded onto the stem and the four hypodermic tubes were led inside the stem and fixed there using hard solder.

4 Calibration Facility

The tunnel used for the calibration was the 229 × 76mm ejector-driven transonic tunnel in the Oxford University Engineering Laboratory. The nozzle used the perforated-wall transonic liners developed by Baines (1983) for calibrating probes for two-dimensional flowfield measurements. Figure 2 is a schematic drawing of the calibration tunnel test section. The stagnation pressure was measured in the upstream plenum and the static pressure was

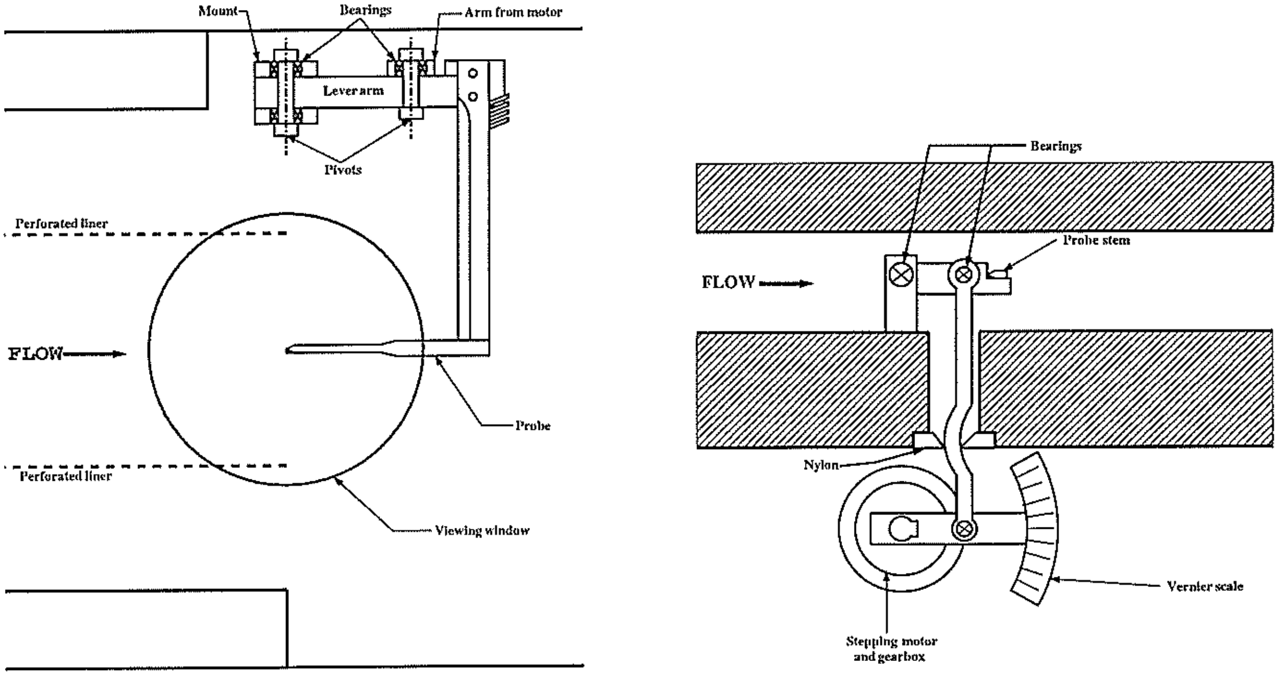


Figure 2: *The Calibration Tunnel.* Left: *Side view;* Right: *Top view.*

measured from tappings in one of the nozzle liners and on the side wall at mid-height at the same axial position as the probe tip. Schlieren flow visualisation was used to check that the tip remained upstream of any shock waves created by the sting or stem of the probe.

A new mechanism was built to automatically traverse the probe through the required range of yaw angles. Since the mechanism was mounted on a circular window, the pitch angle could be set manually between runs. The pivoting mechanism ensured that the probe tip was positioned in the centre of the nozzle exit plane irrespective of pitch and yaw angle. The traversing mechanism was mounted on the window so as to still allow use of the schlieren system in the tunnel. The traversing mechanism was driven by a stepping motor controlled by a 486 PC. This computer also acquired the data for the run using a Computer Boards CIO-DIO24 analogue-to-digital board.

The calibration sequence was to fix the pitch angle, then traverse through yaw angles between -23.6^o and $+23.6^o$, in steps of 1.8^o, at each of 17 Mach numbers, ranging from 0.5 to 1.2. The pitch angle was then varied between -20^o and $+20^o$ in steps of 2^o until all the calibration data had been acquired.

For a given tunnel ejector setting, the flow Mach number varies with probe blockage as the probe pitches and yaws. This does not present a problem as long as the Mach number is recorded at each calibration data point and a sufficient regularly spaced set of Mach numbers is obtained for each combination of pitch and yaw angles. In total, data was acquired at almost 10,000 points of pitch angle α, yaw angle β and Mach number M. See figure 3 for the definition of these flow angles.

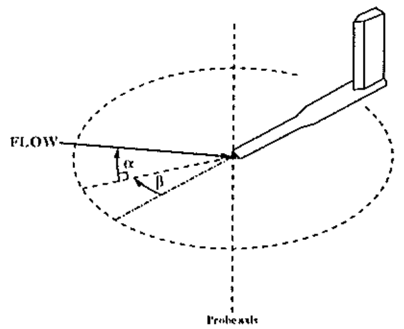


Figure 3: *Definition of flow angles relative to the probe.*

5 Calibration Coefficients

In general, the four probe pressures P_A, P_B, P_C, and P_D are functions of $(\alpha, \beta, M, Re, P_0)$. The truncated pyramid probe is insensitive to Reynolds number (Dominy and Hodson 1992), and so the calibration depends only on (α, β, M, P_0). Dimensionless parameters are then defined to characterise the probe performance. These parameters are *ratios* of pressure, and hence not dependent on P_0. Shepherd (1981) defined a system which divided the area around the probe into six zones for defining his calibration coefficients, due to the desire to prevent the denominator from going to zero and then going negative, causing a pole. Hooper and Musgrove (1991) simplified these coefficients slightly, so that only three zones were required. Both of these systems were devised to allow for measurements of angles in excess of 40 degrees.

It is unnecessary to use this complicated system for calculating the calibration coefficients by either zoning methods for the much smaller range of yaw and pitch angles being considered here. For incompressible flow Sitaram and Treaster (1985) used the following dimensionless parameters (where the hole labelling convention is defined in figure 1):

$$\text{Pitch Coefficient } C_\alpha = \frac{P_B - \frac{1}{2}(P_C + P_D)}{D},$$

$$\text{and Yaw Coefficient } C_\beta = \frac{P_C - P_D}{D},$$

where

$$P_{av} = \frac{P_B + P_C + P_D}{3} \quad \text{and} \quad D = P_A - P_{av}.$$

In the compressible case considered here a third dimensionless parameter is needed. While P_{av}/P_A or D/P_A could be used, it seems logical to use a pseudo mach number based on the measured pressures:

$$\text{Mach number coefficient } C_M = \left(\frac{2}{\gamma - 1} \left[\left(\frac{P_{av}}{P_A} \right)^{-\frac{\gamma-1}{\gamma}} - 1 \right] \right)^{\frac{1}{2}}.$$

Figure 4 shows that C_M varies nearly linearly with Mach number up to a Mach number of approximately 0.9. In transonic flow the slope varies, and so it is necessary to calibrate over finer steps of Mach number in this region. A fourth dimensionless parameter, the total pressure coefficient $C_t = (P_0 - P_A)/D$, is also used later to recover

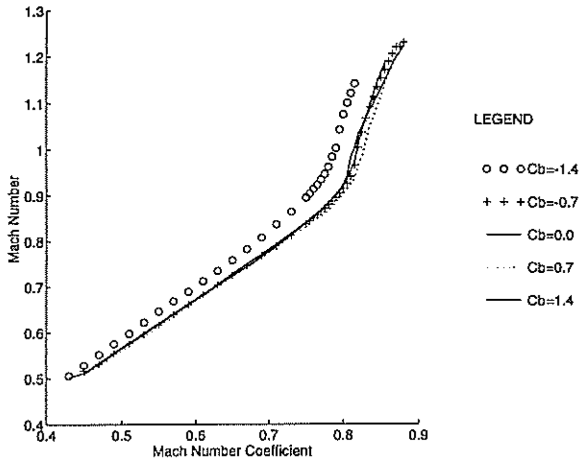
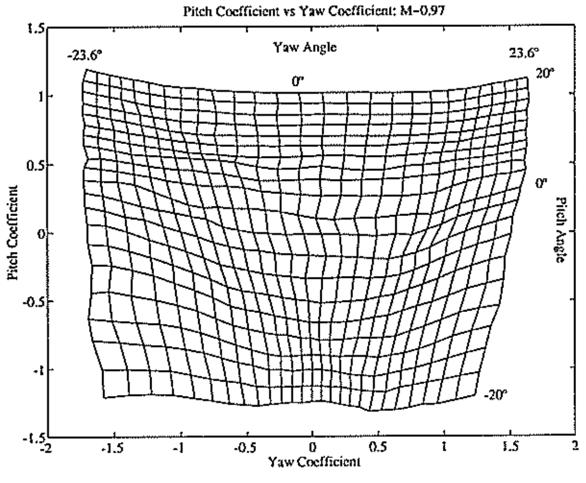


Figure 4: *Variation of Mach number with Mach number coefficient.*

the total pressure P_0. Generally for small α and β, $C_t \approx 0$.

6 Probe Calibration Matrix

The calibration data from all runs of the tunnel was put into one large matrix, the *probe calibration matrix*, in columns of (α, β, M, C_α, C_β, C_M, C_0). This was done in an ordered manner, so that each point could be referenced through a simple indexing algorithm. Figure 5 shows a carpet plot of the C_α and C_β calibration over a range of pitch and yaw angles for a tunnel setting giving $M \approx 0.97$, along with the three dimensional α, β, M surfaces plotted on the C_α, C_β, C_M axes.



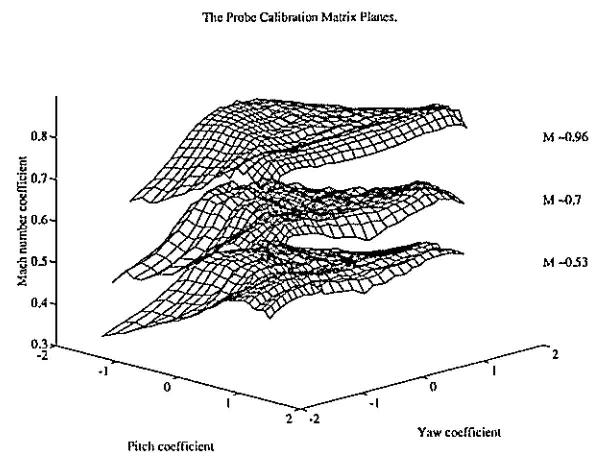


Figure 5: *Planes from the probe calibration matrix.*

7 Transformation to probe application matrix

When the probe is used to measure a flowfield, the probe measurements yield (C_α, C_β, C_M) values. The question then arises as to which is the most efficient computational technique to use the probe calibration data to convert the readings into the flow variables (α, β, M, P_0). A full three-dimensional search for the nearest (C_α, C_β, C_M) points in the *probe calibration matrix*, followed by interpolation is hopelessly inefficient, as, for an $N \times N \times N$ ($N \sim 20$) set of calibrations, $\sim N^3$ ($\sim 10^4$) points have to be searched for each data point.

A more efficient approach is to derive a *probe application matrix* containing values of (α, β, M, C_t) at fixed, regular, known steps of (C_α, C_β, C_M). The eight nearest points enclosing an experimental value of (C_α, C_β, C_M) can then be rapidly determined by a simple indexed *look up*. A simple interpolation then determines the measured flow variables.

Two methods were attempted for transforming the probe calibration matrix into a look-up table at constant values of the three coefficients (C_α, C_β, C_M). Both methods involved defining a grid in probe (C_α, C_β, C_M) space at discrete values of each coefficient and calculating the values of each of the other variables (the three flow variables and the total pressure coefficient) at each point by interpolation. Any points on the new grid lying outside the calibration data range were assigned the value NaN (Not-a-Number).

The first method involved a global search over the whole of the probe space (C_α, C_β, C_M). This was done by dividing the space into the eight octants about the point being searched for. The nearest point in each octant was found using a least-squares searching routine, biased to weight the differing calibration coefficients equally, and the interpolated values of the five variables were found by linear interpolation from these eight points. There were two main problems found with this method. The first was that it was numerically very inefficient, as it searched over every point in the space instead of just the few around the point being considered. This requires $\sim N^6$ ($\sim 10^8$) calculations for the complete transformation. The second problem was that this method sometimes failed to find the actual cell containing the point, if, as regularly happened, the cell failed to lie with each vertex in a different octant relative to the point in consideration. This resulted in increased errors.

Thus a new method was sought to perform the transformation. This employed variable-by-variable (or sequential) interpolation. The principle of this is to do the transformation in three stages, interpolating only one variable at a time. Numerically, this method is considerably more efficient as the searching is done along a line instead of over the whole three-dimensional space. The sequence is summarised as follows:

1. For each fixed α and β combination, interpolate between M and C_M to get the desired C_M grid – this moves the matrix from a uniform grid in (α, β, M) to a uniform grid in (α, β, C_M).
2. For each fixed α and C_M combination, interpolate between β and C_β to get the desired C_β grid – this moves the matrix from a uniform grid in (α, β, C_M) to a uniform grid in (α, C_β, C_M).
3. For each fixed C_β and C_M combination, interpolate between α and C_α to get the desired C_α grid – this moves the matrix from a uniform grid in (α, C_β, C_M) to a uniform grid in (C_α, C_β, C_M), which is the required look-up table.

Thus both methods produce a large output matrix (α, β, M, C_α, C_β, C_M, C_t), the *probe application matrix*, with the variables C_α, C_β, C_M lying on the required grid.

The first method can cope with random measurements in (α, β, M). The second method does not require a constant Mach number grid, but does require constant α and β grids. Both of these methods are applicable to the calibration performed, despite the Mach number not being completely repeatable.

The second method requires only $\sim 3N^3$ ($\sim 10^4$) calculations, and is quicker by a factor of $N^3/3$ ($\sim 10^3$). Using MATLAB software on a UNIX workstation, the second method proved in practice both to be considerably more efficient (a factor of 250 times faster) and to give much smaller average errors when the calibration data was fed back into the *probe application matrix*, provided that a sufficiently fine grid was used to ensure accuracy of the linear interpolations through the transonic region (figure 4 shows the non-linearity of C_M through the transonic region). Consequently, this second method was used to perform the transformation to the probe application matrix. To provide sufficient accuracy on each line interpolation, a grid of almost 87,500 points was selected for the probe application matrix. Despite the size of this matrix, 3,000 points of experimental probe data could be converted into flow variables in just a few seconds. Examples of the planes in the *probe application matrix* are given in figure 6.

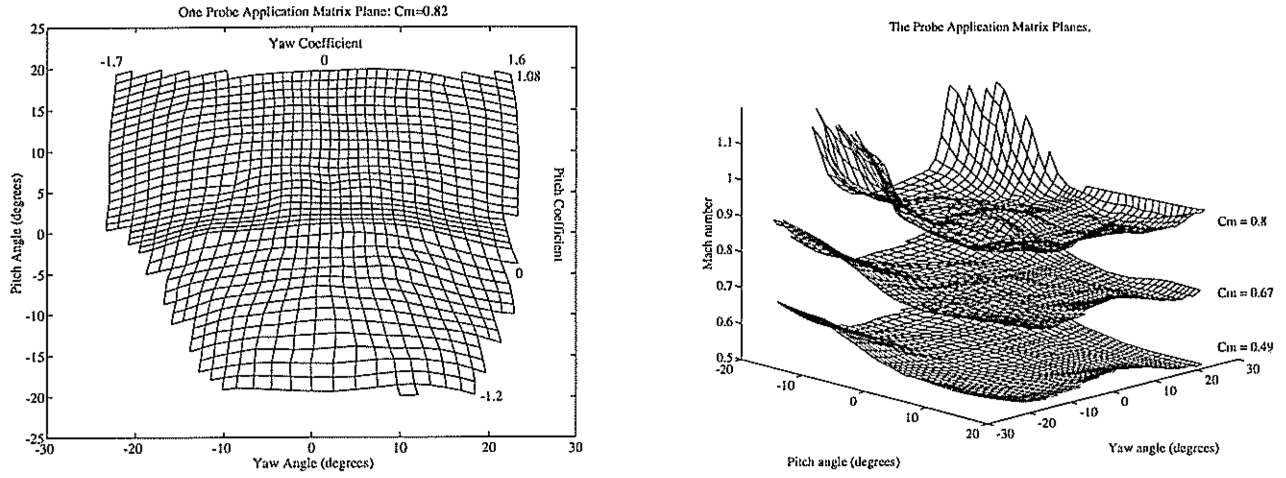


Figure 6: *Planes from the probe application matrix.*

8 Conclusion

A four-hole pyramid probe has been calibrated over a wide range of Mach numbers and flow angles. A new, highly efficient method has been generated for transforming the calibration data into a quick look-up table allowing 3,000 data points to be analysed in a matter of only a few seconds. The computational advantages of this method compared with a simple global search have been evaluated.

9 Acknowledgements

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