Manual for the *coeff* and *flow* programs.

Grant Ingram

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Nomenclature

C_{Ppitch} Calibration pitch coefficient

$C_{Pstatic}$ Calibration static pressure coefficient

C_{Ptotal} Calibration total pressure coefficient

C_{Pyaw} Calibration yaw coefficient

P Pressure

$\overline{P}$ $(P_{left} + P_{right} + P_{bottom} + P_{top})/4$ for five hole probes.

P_{atm} Atmospheric pressure

P_{bottom} Pressure from "lower" hole on three or five hole probe

P_{centre} Pressure from "centre" hole on three or five hole probe

P_{left} Pressure from "left" hole on three or five hole probe

P_{right} Pressure from "right" hole on three or five hole probe

P_{static} Static pressure

P_{top} Pressure from "top" hole on three or five hole probe

P_{total} Total pressure

α Yaw angle

α_{mid} Midspan yaw angle

α_p Primary flow angle

β Pitch angle

1 Introduction

This document describes some programs written to process data from pressure measurements and turn them into flow variables. These programs take the output of a logging file and a calibration file and produce yaw and pitch angles and total and static pressure.

For these programs to be useful you have to have a five hole probe calibration and logging system. These programs are completely re-written versions of programs written by the author for processing data from the so-called "Durham Cascade" a popular turbomachinery test case.

1.1 Source Code

All the code described in this manual is written in a programming language called "Python". To quote the Website[1] Python is:-

> Python is a high-level general-purpose programming language that can be applied to many different classes of problems.

The author chose the Python programming language as it is easy to learn and carries out most of the low level programming details for the user. A useful Tutorial[2] is available on the web, which can also be purchased as a book.[3]

All the source code described in this manual is available under the GNU General Public License which allows the reader to copy, modify and redistribute the code under certain conditions. See the GNU website[4] for more details on the GPL.

1.2 General Principles

The method used for pressure probe measurements in the programs is that of Treaster and Yocum (1979) who describe the use of five hole probes and pressure coefficients. More details of how to carry out the measurements can be found in Ingram (2003). The following is a short introduction to five hole probe measurement techniques, readers who are interested in the operation of the programs should skip ahead to the next section.

This document does not describe the details of the Durham Cascade measurement system however it is worth noting that the programs are designed for differential pressure measurements taken relative to the upstream total pressure - which affects how the flow variables are extracted from the data. For a different set-up modifications would have to be made to the programs. (See Figure 1 for a schematic)

[1]http://www.python.org
[2]http://docs.python.org/tut/tut.html
[3]http://www.network-theory.co.uk/docs/pytut/
[4]http://www.gnu.org/licenses/gpl.html

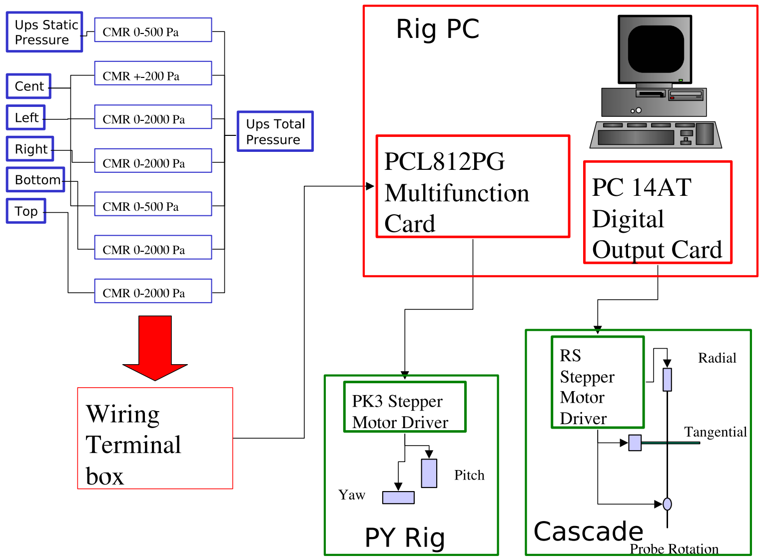

Figure 1: Schematic of Measuring System

The probes used in the Durham Cascade are conventional three and five hole pressure probes. The principle of multi-hole pressure probes is straightforward, in general holes aligned with the flow will read a higher pressure than those that are not. (See Figure 2) With a five holed probe the top and bottom holes will give an indication of pitch angle and the left and right holes an indication of yaw. The exact difference in pressure between two holes depends very much on the individual probe geometry and in general there is no analytical solution to obtain this pressure difference. Therefore in practice the differences have to measured before the probe is used in tests and the information stored in what is normally called a “calibration map”. As well as obtaining yaw and pitch angles a five hole probe can also measure static and total pressure leading to a very complete description of the flow field. The three hole probes could only obtain yaw angles, total pressure and static pressure. If there are large pitch angles present in the flow the probe may not produce accurate readings.

1.2.1 Probe Calibration

In order to produce a calibration map the probe has to be rotated in pitch and yaw through all the expected flow angles to be encountered in the traverse. The response of the probe is measured, recorded and used later to recover the flow variables from the cascade tests.

For three hole probes $\pm 42^\circ$ in yaw was used with increments of two degrees. For five hole probes $\pm 36^\circ$ in yaw and pith with increments of two degrees were typically used. Thus for a three hole probe a calibration consisted of forty three points but for a five hole probe a calibration consisted of 1369 points.

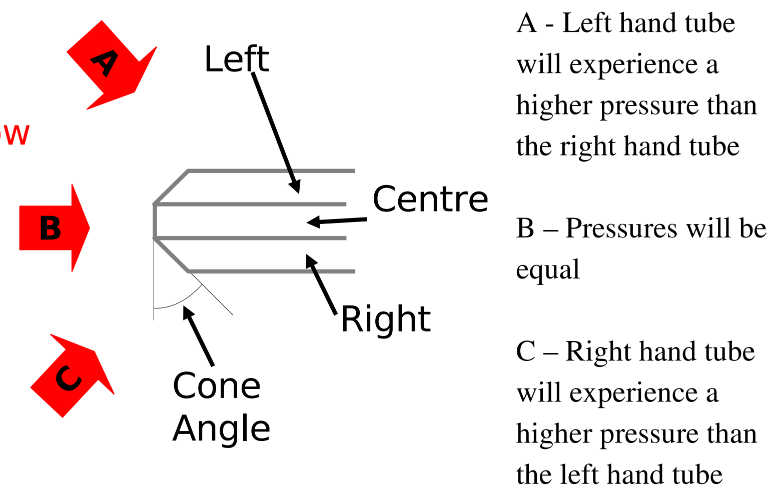

Figure 2: Operation of Multi-tube probe.

The transducers used have a range of ±200 Pa for the centre hole and 0-2000 Pa for each of the outer holes. A 0-500 Pa transducer is used to measure the upstream dynamic pressure. Two additional transducers of 0-500 Pa and 0-2000 Pa are used as extra measurements on the centre hole as when the boundary layer is measured the ±200 Pa transducer has insufficient range. The best ranged transducer is selected during processing in the *calib* program. Clearly some alterations would be needed to the source code if a different set of transducers were used.

The calibration data is made non-dimensional by using the following variables:

$$C_{Pyaw} = \frac{P_{left} - P_{right}}{P_{centre} - \overline{P}} \tag{1}$$

$$C_{Ppitch} = \frac{P_{bottom} - P_{top}}{P_{centre} - \overline{P}} \tag{2}$$

$$C_{Ptotal} = \frac{P_{centre} - P_{total}}{P_{centre} - \overline{P}} \tag{3}$$

$$C_{Pstatic} = \frac{\overline{P} - P_{static}}{P_{centre} - \overline{P}} \tag{4}$$

where

$$\overline{P} = (P_{left} + P_{right} + P_{bottom} + P_{top})/4 \tag{5}$$

for five hole probes. For three hole probes C_{Ppitch} does not exist and

$$\overline{P} = (P_{left} + P_{right})/2 \tag{6}$$

Once a complete probe calibration has been obtained a test in the cascade may be conducted.

1.2.2 Recovery of Flow Variables.

In order to take measurements a data logging run is carried out where the probe is placed in a flow of interest and readings taken at a number of points. An automated system such as that found in the author's thesis (Ingram (2003)) can involve over a thousand points in each measurement.

The experimenter is then left with two data files, a file with measurements about the probe calibration and a file with measurements in the flow situation of interest. The programs to carry this out are the subject of this manual.

2 How to use the Programs

This section describes how to use the programs to manipulate a set of data from raw pressure format into pitch averaged form.

For this example we have a set of raw data from our calibration test which is in the file *calib.pa*. We also have a set of raw data from the test which contains the pressure measurements around the geometry of interest this file is called *data.pa*. How to obtain these files is not covered here - you need some sort of test rig. The first step is to produce a calibration file using *coeff*.

The first step is to ensure that a modern version of the Python interpreted language is installed on your system. Most modern Unix and GNU/Linux systems will have a version installed by default and a Microsoft Windows version is also available. See The Python Download Site[5] site for more details.

The programs found here are all command line versions, the following shows what you need to type:

```
$ python coeff.py --data=calib
```

This isn't very descriptive so you can run the program with the verbose option:

```
$ python coeff.py --data=calib --verbose
coeff 1.0 Copyright (C) 2005 Grant Ingram.
        This program comes with ABSOLUTELY NO WARRANTY; for details
        use option --license.  This is free software, and you are
        welcome to redistribute it under certain conditions.

Reading data from calib.pa
Writing data to calib.cal
Probe Code:  5.0
Dynamic Correction: 1.01645142716
n_pitch_points: 37.0
n_yaw_points: 37.0
n_points: 1369.0
```

The end result is the same in both cases. A file called *calib.cal* containing the calibration for the data in question. The next step is to run the calibration data and the pressure measurements through the *calib* program.

The *flow* script does most of the real work.

Running it is straight forward:-

```
$ python flow.py -d data -c calib -o results
```

Again a more verbose option is available, if the command line options are unclear, online help is available!

[5] http://www.python.org/download/

```
$ python flow.py --help
usage: flow.py [options] arg

options:
  --version             show program's version number and exit
  -h, --help            show this help message and exit
  -dDATANAME, --data=DATANAME
                        sets measurement filename root to dataname
  -cCALIBNAME, --calib=CALIBNAME
                        sets calibration filename root to calibname
  -oOUTNAME, --output=OUTNAME
                        sets output filename root to outname
  -v, --verbose         outputs lots of information
  -q, --quiet           operates silently (default)
  -l, --license         prints out copyright information
```

There is an additional program which only works on Unix systems which plots out calibration maps this is called *plotcoeff* and requires the Biggles plotting software to function. See the Biggles website[6] for more details.

[6] http://biggles.sourceforge.net/

3 The *coeff* program

This program is extremely simple, it reads the selected file in and calculates a series of pressure coefficients for a five hole probe and then writes the data out. *coeff* accepts "GNU" style command line options.

Input files required:-

- Calibration data, default: *calib.pa*

Output files produced:-

- Data output, default: *calib.cal*

3.1 Operation of Program and notes on design.

The program operates in a very straightforward manner:-

- the data files are opened
- data is read in and a correction factor to account for different total pressure values measured by the multi-holed probe and the reference pitot-static probe is applied. This is get around the fact that the calibration jet in the authors facility is quite small.
- each pitch and yaw point is cycled through and the calibration coefficients are calculated
- data is then written to file

The best ranged transducer on the centre hole is selected for use at each data point, i.e. if the range of the ±200Pa transducer is exceeded the 0-500Pa transducer will be used instead. This again is a feature from the specific hardware arrangements in the authors cascade.

4 The *flow* program

This program is more complex it does the bulk of the work in recovering flow variables. *flow* accepts “GNU” style command line options.

Input files required:-

- Calibration data, default: *calib.cal*
- Measurement data, default: *press.pa*

Output files produced:-

- Data output, default: *flow.t5c*

4.1 Operation of Program and notes on design.

The program operates in the following manner, for more detailed information consult the source code of the program! This is intended as a general guide as to what it does. Some of the algorithms are then described in more detail.

- command line arguments are processed
- the calibration file data is read in
- the measurement data is read in to memory
- the flow variables are calculated
  - Each measured valued in the file is stepped through
  - calibration coefficients are calculated for each value
  - Pitch and Yaw angles are calculated from the data
  - Using these pitch and yaw angles, total and static pressure are calculated from the data
- the output is written to file

Note that this program relies on calibration data being presented in a systematic manner, with pitch angle held constant and yaw angle then varied. Without this arrangement of data the program will fail! i.e. the calib.cal file should be in the following order:-

```
Pitch Yaw ...
-30 -30 ...
-30 -20 ...
-30 -10 ...
-30 0 ...
-30 10 ...
```

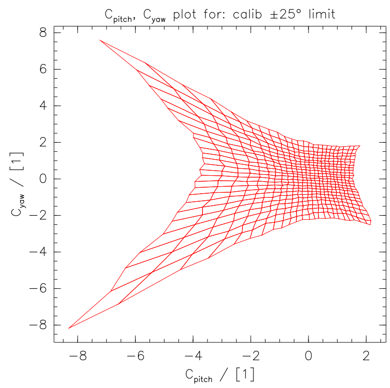

Figure 3: Five Hole Probe Calibration Map (Probe 5HA)

```
-30 20 ...
-30 30 ...
-20 -30 ...
-20 -20 ...
-20 -10 ...
-20 0 ...
-20 10 ...
-20 20 ...
-20 30 ...
... ... ...
```

The best ranged transducer on the centre hole is selected for use at each data point, i.e. if the range of the ±200Pa transducer is exceeded the 0-500Pa transducer will be used instead. This again is a feature from the specific hardware arrangements in the authors cascade.

4.1.1 Pitch and Yaw Angle Recovery

A five hole calibration map is illustrated in Figures 3. The "vertical" lines in Figure 3 are lines of constant pitch angle and the "horizontal" lines are for constant yaw. Note how the map becomes "stretched" at the edges as $P_{centre} \approx \overline{P}$.

Data can be extracted as follows: C_{Pyaw} and C_{Ppitch} can be calculated from the pressure data directly. The point will lie in a "box" formed by the lines of constant yaw and pitch angle on the calibration map. This box is found by the program and the value of yaw and pitch angle estimated by linear interpolation.

To calculate the yaw and pitch angle for each measurement point the following procedure is used:-

- each "box" in the calibration map is found
- a "Fence Crossing" test is conducted to determine whether the point is in the box

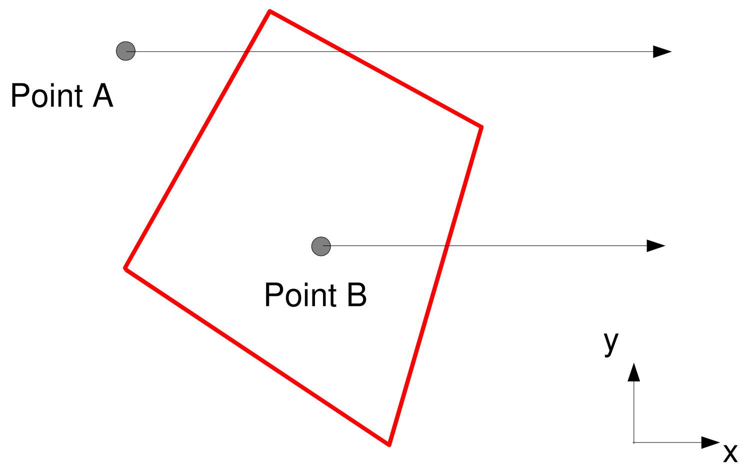

Figure 4: "Fence crossing" algorithm for box-test.

- when the box the measurement point is in is found a linear interpolation is conducted to determine pitch and yaw values

The "Fence Crossing" Test In order to determine whether a point is inside a box or not the "fence crossing" algorithm is used. A line is drawn from the point in question to infinity and the number of times this line intersects with the vertices of the box is calculated. If the line intersects with the vertices an odd number of times then the point lies within the box, an even number of intersections indicates that the point lies outside the box. This is illustrated in Figure 4 where point A is outside the box (two crossings) and point B is inside the box (one crossing).

Interpolation for Pitch and Yaw The following is used to calculate the pitch and yaw angle from the data. Figure 5 which shows the arrangement of an irregular "box" around a measurement point. Consider a quantity γ such that:-

$$\gamma_0 = \gamma_1 = \gamma_I \tag{7}$$

$$\gamma_3 = \gamma_2 = \gamma_J \tag{8}$$

and also note that:-

$$y_I = y_J = y_m \tag{9}$$

If $\gamma \equiv \beta$ and $x \equiv C_{Ppitch}$ and $y \equiv C_{Pyaw}$ then this situation is identical to that of finding the pitch angle in our calibration map. The notation used here is the same as that used in the program.

Interpolation is linear:-

$$\gamma_M = \gamma_I + \left(\frac{x_m - x_I}{x_J - X_I} \right) (\gamma_J - \gamma_I) \tag{10}$$

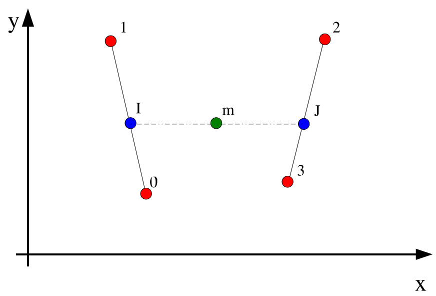

Figure 5: Labelling for "semi-bilinear" interpolation.

where x_I and x_J are found as follows:-

$$x_I = x_0 + \left(\frac{y_M - y_0}{y_1 - y_0}\right)(x_1 - x_0) \tag{11}$$

$$x_J = x_3 + \left(\frac{y_m - y_3}{y_2 - y_3}\right)(x_2 - x_3) \tag{12}$$

If we make an appropriate substitution of variables we can obtain α from the same logic. This routine is called "semibilinear" in the code as it's not quite bilinear interpolation - there is probably a formal name for this or a better way of doing this but I haven't yet been able to find it!

4.1.2 Total and Static Pressure Recovery

Total and Static pressure recovery is much more straightforward as the grids are all rectangular. The procedure is as follows:-

- Determine the coordinates of a box bounding the pitch and yaw values found
- Perform bilinear interpolation to determine values of C_{Ptotal} and $C_{Pstatic}$
- Calculate P_{total} and P_{static}

Bilinear Interpolation Consider a regular grid of points with a measurement point located inside them shown in Figure 6. Consider a quantity γ which is different at each point this time. Then if $\gamma \equiv C_{Ptotal}$ and $x \equiv \beta$ and $y \equiv \alpha$ we have a situation equivalent to finding C_{Ptotal}. This can be calculated as follows:-

$$\gamma_M = \gamma_I + \left(\frac{x_m - x_I}{x_J - X_I}\right)(\gamma_J - \gamma_I) \tag{13}$$

where γ_I and γ_J are found as follows:-

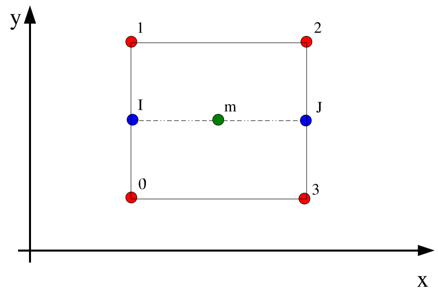

Figure 6: Labelling for bilinear interpolation.

$$\gamma_I = \gamma_0 + \left(\frac{y_I - y_0}{y_1 - y_0}\right)(\gamma_1 - \gamma_0) \tag{14}$$

$$\gamma_J = \gamma_3 + \left(\frac{y_J - y_3}{y_2 - y_3}\right)(\gamma_2 - \gamma_3) \tag{15}$$

Total and static pressure can then be calculated directly:-

$$\overline{P} = (P_{left} + P_{right} + P_{bottom} + P_{top})/4 \tag{16}$$

$$P_{total} = P_{centre} - C_{Ptotal}(P_{centre} - \overline{P}) \tag{17}$$

$$P_{static} = \overline{P} - C_{Pstatic}(P_{centre} - \overline{P}) \tag{18}$$

References

Ingram, G. (2003). Manufacture of the third generation endwall. Technical report, School of Engineering, University of Durham.

Treaster, A. and Yocum, A. (1979). The calibration and application of five hole probes. *ISA Transactions*, 18(2):23.

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