Paper 2

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THE CALIBRATION OF FAST RESPONSE AERODYNAMIC PROBES IN A TRANSIENT FACILITY

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ABSTRACT

The use of aerodynamic probes for measurements of Mach number and direction within turbine simulation facilities is proving to be a powerful and robust technique. Recent work at Oxford has concentrated on the devising and construction of fast response aerodynamic probes where semiconductor sensors are directly mounted on the surface of the probe. This has enabled greater flexibility in the design and construction of probes, and has maximised the available bandwidth of measurements made. Before any probe may be utilised it must undergo extensive calibration. Obviously the precision of these two processes affects the ultimate accuracy achievable with the probe measurements, as does the analytical method employed in applying these calibrations.

In this paper a dedicated probe calibration facility is described in which the yaw and pitch angles are systematically varied whilst Mach and Reynolds numbers are maintained constant. This facility uses a fixed compressed air supply to drive a free jet for short duration calibration runs and thereby avoids the large overhead costs associated with a continuous flow facility.

In the case of a three-dimensional aerodynamic probe, confirmation of sensor measurement integrity results from the building up of probe aerodynamic performance over a considerable number of runs.

INTRODUCTION

Aerodynamic probes have been used for several decades in turbomachinery related research in order to determine fluid flow total and static pressures. Combination type probes enable flow Mach number and direction to be measured from the pressure field around the probe. To use this type of instrumentation careful calibration of the probe is at first carried out in some form of calibration facility before the probe is introduced into the experiment where measurements of flow quantities are required.

Advances in semiconductor sensor technology have made it possible to make unsteady aerodynamic measurements with these probes, whereas traditionally they have only been possible with hot wire or optical techniques. The Oxford Rotor, Ainsworth et al [1988], is a transient rotating turbine simulation facility and will be used as an example of a flow field to be investigated.

Collaboration with Kulite Semiconductor Inc. over recent years has allowed Oxford to develop techniques for mounting pressure sensors on turbine blades. Theses techniques have now enabled the fabrication of miniature semiconductor aerodynamic probes. These have been found to permit a more compact and flexible design of the probe, and since the pressure sensing element is mounted on the probe surface, wide bandwidths are possible.

The pressure transducers used for this work have been tested for bandwidth using shock tube techniques and found to be in excess of 100kHz even when protected by a silastomer coating Ainsworth and Allen[1990]. Electrical calibration of each sensor is necessary to establish pressure sensitivity, temperature sensitivity, and temporal stability. Compensation techniques for these effects using software can then be applied.

In the current work a pressurised transonic nozzle is used for the aerodynamic calibration of these probes at combinations of yaw, pitch and Mach number, where the Reynolds number for the Rotor is also matched.

NOMENCLATURE

C_{Mach}	Mach coefficient
C_{Pitch}	Pitch coefficient
C_{Yaw}	Yaw coefficient
C_{Pt}	Total pressure coefficient
Mn	Mach number
P_c	Critical Pressure
P_t	Total Pressure
R_b	Transducer bridge resistance
Re	Reynolds number
T	Temperature
V_o	Supply voltage
α	Fractional change in resistance with temperature
θ	Yaw angle
ϕ	Pitch angle

CALIBRATION FACILITY

Calibration facility layout is shown in Figure 1 and a description of each component follows. The flow enters the tunnel from the lower right of the Figure 1, passes through a series

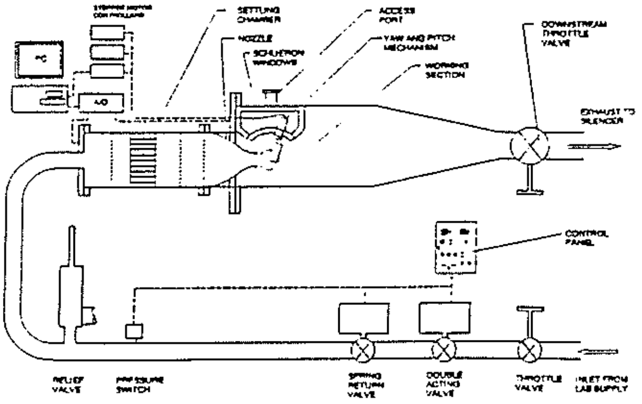


Figure 1 Calibration tunnel schematic

of control valves and then turned through 180 degrees before entering the main working section and acceleration through the nozzle.

Air control

The laboratory air supply consists of a main reservoir tank compressed to 28 bar. This provides the source of air which may be bled off for short durations and can maintain a constant Mach number in the Nozzle for up to 60 seconds.

Control of the rig air supply incorporates a number of safety features. An upstream hand operated gate valve allows isolation of the rig from the main air supply. This valve also has a smaller maximum diameter than the nozzle to ensure the latter does not become choked.

Primary flow control is achieved by two parallel ball valves in line downstream of the gate valves. The first is operated by a double acting pneumatic actuator with the air supply electrically operated through control solenoids. This allows the valve to be opened or closed in less than a second.

The second ball valve is operated through a spring return pneumatic actuator. This valve allows the tunnel flow rate to be set. The spring return mechanism also has the safety feature that should air supply fail the ball valve is automatically closed.

Over-pressure in the rig is prevented by an IMI Birkett full lift safety valve with release pressure set at 10 bar. Futhermore, an electrical pressure safety switch is located on the pipe work linked to the control box to close the two ball valves in the event of tunnel over-pressure.

Settling chamber

Before the flow enters the nozzle it is expanded into a settling chamber. The flow enters the settling chamber through an abrupt expansion which, although causing a small loss of total pressure, does have the advantage of reducing the length required. The flow is then directed through a module of flow straighteners, dividing the flow and breaking up any large eddies into smaller eddies moving in the correct direction.

A final set of gauzes breaks up any remaining eddies and reduces any boundary layers at entry to the nozzle.

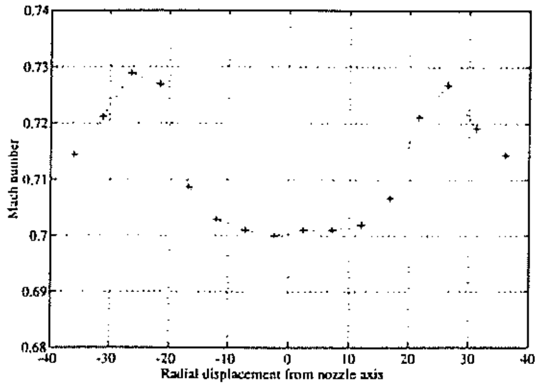


Figure 2 Nozzle Mach number profile

Nozzle

The nozzle is required to reduce mean flow non uniformities, turbulence and, by allowing a reduced upstream velocity all screen losses are minimised. The nozzle profile was designed on the principles outlined by Morel [1975] using two matched cubic equations and machined from a single piece of Dural bar. The nozzle has a diameter of 50mm and an area contraction ratio of 12.96:1.

A traverse of the nozzle profile, Figure 2, shows how the Mach number varies in the radial direction. The central core region gives an ample region of uniform flow for calibration. This traverse was achieved using a fine needle static probe, the design taken from Bryer and Pankhurst[1971]. The isentropic Mach number was derived using the measured static and the upstream total pressure.

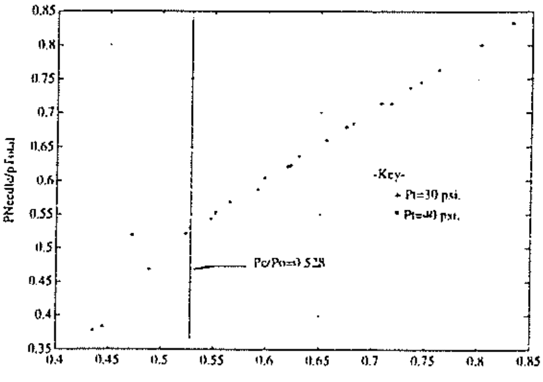


Figure 3 Comparison of sidewall and needle probe measured pressure ratio

To verify that the Mach number measured during the run corresponds with that experienced by the probe, a comparison of the pressure ratio measured by the nozzle exit static tapping with that of the needle probe was made. The comparison, plotted in Figure 3, shows excellent agreement up to the critical pressure ratio but above Mach 1 the values no longer agree. The Mach number measurement from the side tapping may therefore be applied with confidence up Mach 1.

Working section

The working section consists of a large external pressure vessel suspended from a supporting frame. The front flange of the pressure vessel may be unbolted and rolled back on the supporting frame for access into the working section. On the front flange are mounted the nozzle and probe positioning traverse mechanism.

By using a pressurised working section the nozzle exit static pressure can be raised above atmospheric pressure permitting probes to be tested over a range of Mach and Reynolds numbers. The pressure rise is achieved by restricting the air flow at exit using a hand control valve.

By closing the exit valve the whole rig may be pressurised for static electrical calibration of both rig and probe instrumentation before probe calibration commences. A mechanical interlock prevents upstream valves from opening with the exit valve closed.

Traverse Mechanism

Probes are positioned one diameter downstream of the nozzle using a stepper motor traverse mechanism controlled by from a PC. The mechanism was designed to yaw the probe up to ±90 degrees and to ±30 degrees in pitch. Using a circular track the mechanism is designed to rotate about the front face of the probe whilst maintaining a constant position relative to the nozzle.

Bentham 23-301 stepper motor system and controller are used to allow accurate positioning of the probe. Care with screening is necessary and earthing is to a single point to ensure minimum noise from interference.

Instrumentation

Instrumentation for the calibration facility is designed primarily for automated logging of readings by computer. The instrumentation can be divided into two categories. The first half consists of all the rig diagnostics before and during calibration and are monitored by a dedicated IBM compatible PC. This uses a CIL Microsystems interface unit incorporating a 16 bit A/D and operating through an IEEE-488 interface. These readings enable the first PC to display the Mach number, total pressure, probe position and rig temperatures during calibration.

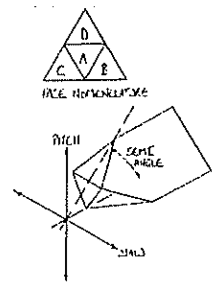
A second separate IBM compatible PC with a high specification 16 bit A/D board is used to record the values from the pressure transducers on the aerodynamic probe during calibration. The data is recorded directly onto the A/D board's 2Mb of memory and downloaded to the computer after the experiment. This system is fast (400kHz) and a large number of data points may be recorded. To avoid noise pick up between signal and the A/D board the initial signal is amplified close to the signal source. The AD524 differential input instrumentation amplifier was chosen for this application because of its wide bandwidth (200 kHz) and low noise.

The results from each traverse of a probe can be immediately processed using the commercially available MATLAB software package.

MATLAB has been a particularly useful package for this application since it combines a large range of in built maths functions with the flexibility to incorporate in house software. This has allowed a suite of dedicated programs to be written which can quickly process the data. Throughout calibration the emphasis is on early diagnosis of problems with on line processing.

PROBE CALIBRATION

In order to use an aerodynamic probe to determine flow velocity (Mach number and angle), it must first be calibrated in a flow at dimensionally similar conditions. For compressible flows of interest here,the relevant non-dimensional parameters are Reynolds number and Mach number. One of the design objectives of the three dimensional aerodynamic probes in question, Ainsworth et al [1994], was to produce a probe with minimum sensitivity to Reynolds number, simplifying the calibration procedure. For a probe insensitive to Reynolds number, it would be sufficient to determine the probe's aerodynamic coefficients as functions of pitch and yaw angle, and flow Mach number. Using a spherical coordinate system flow Mach number and direction may be expressed as Mn, θ and ϕ.



For a four port three-dimensional aerodynamic probe the calibration coefficients used in this work are as first proposed by Sitaram and Treatser[1985], but extended to include a Mach coefficient to allow for compressibility.

$$C_{yaw} = \frac{pB - pC}{pA - \frac{(pB+pC+pD)}{3}}$$

$$C_{pitch} = \frac{pD - (\frac{pB+pC}{2})}{pA - \frac{(pB+pC+pD)}{3}}$$

$$C_{Mach} = \left[\frac{2}{\gamma-1} \left[\left(\frac{\frac{pB+pC+pD}{3}}{pA} \right)^{-\frac{(\gamma-1)}{\gamma}} - 1 \right] \right]^{0.5}$$

In addition to these three primary coefficients, a total pressure coefficient may be derived to allow total pressure measurement to be made when the flow Mach number and direction have been found.

$$C_{Pt} = \frac{(P_t - pA)}{pA - \frac{(pB+pC+pD)}{3}}$$

The form of the Mach coefficient adopted here has been used since it creates a calibration grid linear with Mach number. This has the advantages for linear interpolation used in the inversion algorithm, Main et al [1994].

Examination of the primary non-dimensional groups used in calibration will reveal that they are independent of the total pressure. This means that small variations in total pressure can be tolerated during calibration.

The calibration method described uses a large reservoir of air, but as the air flows out of the calibration tunnel the total pressure in the main tank will drop. However the total pressure drop will not affect the calibration provided the Mach number is maintained.

Reynolds number dependency has been the subject of much earlier work, for instance Dominy and Hodson [1990]. The general consensus has been that the prismatic geometries of the Wedge and Pyramid probes are superior in this aspect and show little Reynolds number dependence.The surface mounted semiconductor probes also have the advantage of avoiding any tapping in the probe surface which have been associated with certain Reynolds number features.

Calibration using a free jet has the advantage that the geometry simulates the configuration when taking measurements at a turbomachine exit. The intrusive nature of the probe in the jet is therefore matched by the probe when recording the measurements of interest.

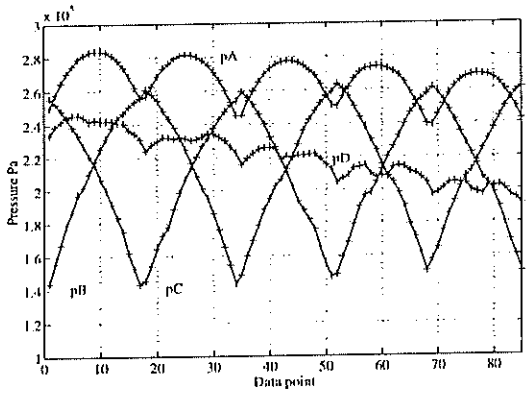


Figure 4 Calibration run data

Calibration procedure

Each probe needs to be calibrated for combinations of Mach, yaw and pitch angle. In this facility the flow is maintained at constant Mach number whilst the probe is traversed in incidence.

The plot in Figure 4 shows the data obtained in one calibration run in approximately 45 seconds. This data was recorded during the calibration of a three-dimensional probe based on the pyramid geometry of Shepherd [1981]. With the flow set to constant Mach number, in this case Mach 0.7, the probe traverses through 17 positions in yaw for each of 5 positions in pitch. This makes a total of 85 points per calibration run. For each point the transducers are sampled 1000 times so that any noise and aliasing can be removed through averaging.

Throughout the calibration the rig conditions are also monitored and for this calibration run are plotted in Figure 5. The first point to note is the constancy of the Mach number with time despite the slight drop in total pressure, satisfying our earlier requirement. The Reynolds number, based on the probe head pitch circle diameter, is also almost constant.

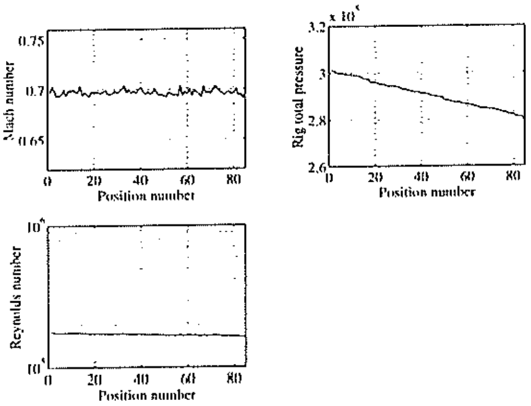


Figure 5 Calibration run diagnostics

During calibration the temperature of the probe changes from the cooling effect of the air flow. The surface mounted transducers are subject to this temperature change and its effects must be considered. Any temperature influences on the transducer output are readily accommodated through electrical calibration and correction, as detailed later in this paper.

With temperature effects removed, the recorded pressures can be converted into coefficients. These are plotted in Figure 6. For this data corresponding to low pitch angle, the mach coefficient and yaw coefficient are almost independent of pitch angle and almost collapse onto one line. The total pressure coefficient is also plotted from which the total pressure may be found and static pressure derived once the Mach number is known.

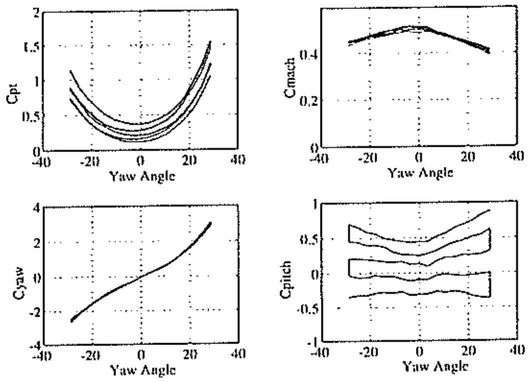


Figure 6 Derived coefficients

The range of experimental flows to be encountered determines how many of these calibration runs are required for a complete calibration map. Three calibration runs combined will give a nominal range of 30 degrees in yaw and pitch at one Mach number. Repeating over a series of Mach numbers,typically 0.3 to 0.9 in 0.05 Mach intervals, a complete calibration space of C_{Mach}, C_{yaw} and C_{pitch} against Mn, θ and ϕ is built up. In Figure 7, the calibration data has been inverted and plotted for one value of Mach coefficient. From this plot

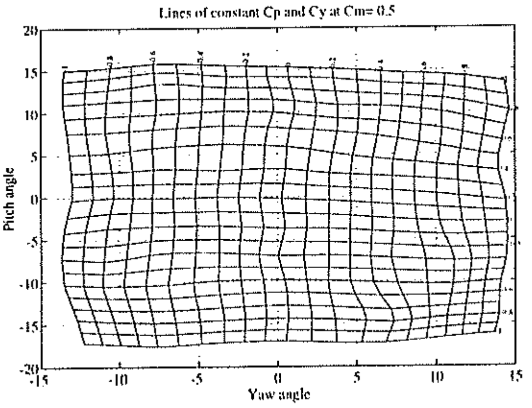


Figure 7 Pitch and yaw angles plotted along lines of constant pitch and yaw coefficients

experimental values of pitch and yaw can be found. This is readily extended to Mach number when the Mach coefficient is also included.

The integrity of the probe and calibration method are demonstrated by the ability to achieve reliable calibrations over a series of runs.

ELECTRICAL CALIBRATION

Introduction

The semiconductor strain gauge pressure transducer is a highly robust linear pressure sensor. The transducer consists of a silicon diaphragm which is bonded to a supporting pillar. The underside of the diaphragm is micro etched creating an evacuated cavity between it and the supporting pillar whilst a Wheatstone resistor bridge is diffused onto the upper side. When the diaphragm deflects under pressure the strain in the resistors causes them to change in value giving an bridge output voltage. By careful matching and positioning of the resistors, good linearity with little hysteresis can be achieved. These have been successfully used in a variety of applications and, at Oxford in particular, they have proved to be most suitable for wide bandwidth pressure measurement.

Care must be taken to avoid the effects of changes of resistance in the semiconductor due to anything other than pressure since these which would clearly cause errors. In practice, the main source of error is caused by the influence of temperature on the resistance values. The transducer designer attempts to minimise any temperature variation be careful matching of the temperature coefficients of resistance of the bridge elements. Additional temperature compensation can be applied with external circuitry to the transducer bridge and in commercial transducers this hardware temperature compensation is included in the packaging of the transducer.

The simplest hardware compensation scheme starts with the use of a resistor in series with the bridge, known as a span resistor, to correct overall span variation of the transducer. This scheme works only if the bridge output is decreasing with temperature. At the same time as any output drop with temperature, the overall bridge resistance will be increasing. The voltage distribution with the series resistor will therefore act to increase voltage across the bridge, increasing the bridge output and thereby compensating for the span variation. Careful selection of the value of the series resistor would minimise any temperature variation.

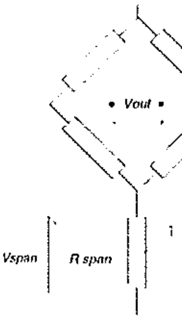


Figure 8 Temperature compensation circuit

For the work at Oxford the standard packaging for the chip, incorporating any compensation hardware, has been removed in order to minimise size. However by using an uncomplicated circuit and external software correction, good temperature rejection can be achieved.

Implementation of this technique is facilitated by considering the transducer performance relative to a reference temperature, usually taken to be 25C, and correcting the output voltage to the value that would have been recorded if the transducer had remained at this reference temperature. With this correction incorporated into the voltage, the value of the coefficients at the reference temperature can be applied to find the measured pressure.

In the circuit diagram shown in Figure 8, a span resistor external to the transducer is used and trimmed at the reference temperature until bridge excitation is half the supply voltage, V_o. The bridge in series with the span resistor acts as a potential divider. As the bridge resistance varies, any small changes in the bridge resistance as a result of temperature changes will be accurately measured by the change in V_{span}. This voltage change, termed V_{sense}, is a measure of the transducer temperature.

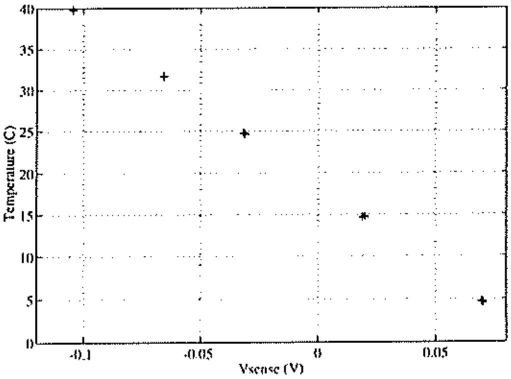


Figure 9 Variation of Vsense with temperatue

Derivation

The relationship between V_{sense} and Temperature may be derived if at first we assume a first order increase in resistance of the bridge with temperature. After connecting the bridge, at the reference temperature 25C, the span resistor is trimmed until bridge excitation is half supply voltage, thereby setting the span resistor to the same resistance as the initial bridge resistance. Incremental temperature changes can now be considered from this reference point.

Initial values:
R_{bo} Bridge resistance at 25 deg C
R_s Span resistance
At 25C set $R_s = R_{bo}$ such that bridge excitation is $Vo/2$
Now consider an increase in temperature T:

$R=R_o(1+\alpha\Delta T)$
This gives rise to a V_{sense}:

$$V_{sense} = V_{span} - V_{span_o} = V_o \left[\frac{R_s}{R_s+R_{bo}(1+\alpha\Delta T)} - \frac{R_s}{R_s+R_{bo}}\right]$$

Rearranging for T using the relationship that $R_{spano}=R_{bo}$:

$$\Delta T = \frac{1}{\alpha} [\frac{-4 V_{sense}}{2 V_{sense} + V_o}]$$

Since $V_{sense} << V_o$ for small temperature changes this may be approximated as :

$$\Delta T = \frac{1}{\alpha} [\frac{-4\ V_{sense}}{V_o}]$$

The calibration of V_{sense} against temperature shown in Figure 9 confirms the first order approximation originally taken.

Calibration

The transducers are calibrated over a wide range of pressures and temperatures. A Druck DPI501 digital pressure transducer, linked to an environmental chamber and controlled via the IEEE bus interface by a dedicated computer, is used to run the transducer through a standardised cycle. The pressure sensing element for the DPI501 is a vibrating cylinder pressure transducer manufactured by Schlumberger, measuring to an accuracy of 0.007% full scale. In the calibration the transducer is cycled from 200mB to 3500mB in five steps, three times at 25C, 5C, 15C, 25C, 32C, 40C and finally 25C again. Repeating at each temperature three times gives an indication of any hysteresis and also by returning to 25C three times during the test gives the overall repeatability. Allowing for generous settling time this whole test cycle lasts approximately 14 hours. Figure 10 shows typical results from one of these calibration cycles.

The Kulite sensor is highly linear and a first order model of its behaviour is quite satisfactory. The measured pressure is therefore given as follows:

$P = S_o V_{out} + O_o$

where S_o sensor span at 25 deg C

O_o sensor offset at 25 deg C

The influence of temperature on the transducer output is accommodated from the variation of the coefficients in equation 6 with temperature as found in the calibration cycle.

span sensitivity $= dS/dT$

offset sensitivity $= dO/dT$

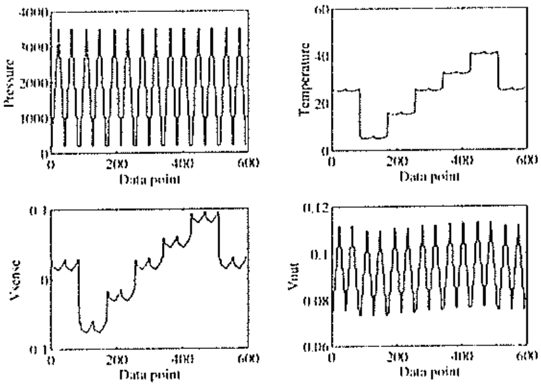


Figure 10 Electrical calibration

PROBE APPLICATION

Measurements at turbine exit

The 45 degree pyramid probe with the calibration discussed earlier was mounted downstream of the HP turbine of the Oxford rotor facility. The rotating assembly is un-braked and the turbine accelerates during run time, Figure 11, and consequently the flow incidence changes with time. At the point at which the rotor passes through design speed a fast data acquisition system is triggered to record unsteady parameters.

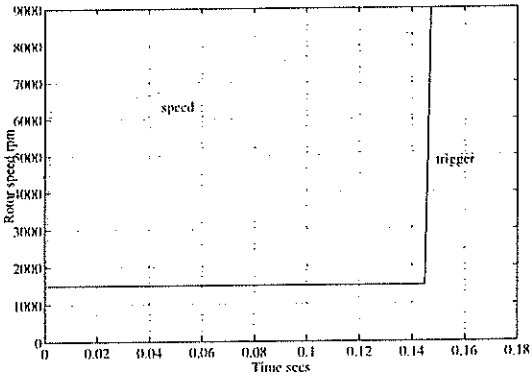


Figure 11 Rotor speed variation during run

The pyramid probe was used to monitor this incidence change with speed. The probe was mounted at 19 degrees to the axial direction, with this being the indicated mean flow direction at turbine exit in the absolute frame of reference from through-flow analysis. In this experimental set up the yaw axis corresponds to circumferential flow, whilst the pitch axis measures radial flow.

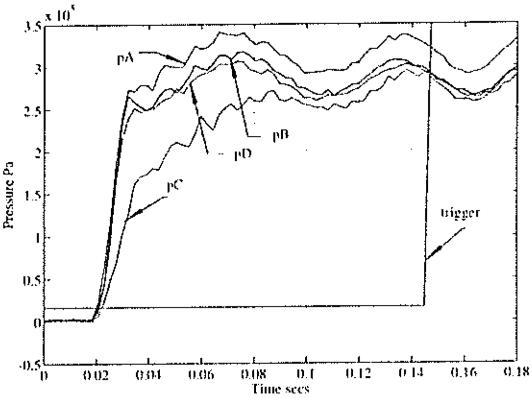


Figure 12 Pyramid probe face pressures

Data was sampled at 400Hz throughout the 200 ms run and the raw pressures recorded from the probe during the run up are plotted in Figure 12. Each of the pressures from the four faces, A to D, are plotted and an oscillation in the total pressure associated with the isentropic piston which supplied the driving flow can be clearly seen. The pressure difference between faces B and C is a function of the yaw angle. As this pressure approaches zero the mean flow approaches the design point flow angle.

Applying the probe aerodynamic calibrations yields the yaw, pitch and Mach number as measured by the probe and is shown in Figure 13. The yaw angle change with time is clearly illustrated and the flow relative to the probe is near zero at design point, confirming the prediction from flow through analysis. The flow in the rotor is predominately axial and would therefore be expected to have little pitch component and this is borne out by the measurements.

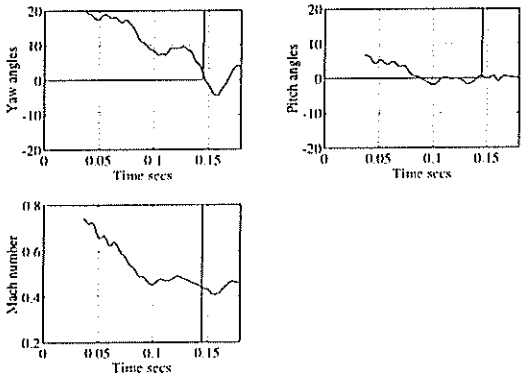


Figure 13 Measured flow parameters

CONCLUSIONS

Aerodynamic probes with surface mounted transducers are a powerful technique for measurements in turbomachinery applications. Each probe requires thorough calibration before use in an experiment. This paper demonstrates how both the electrical and aerodynamic calibration may be undertaken for the surface mounted semiconductor fast response probes manufactured at Oxford.

A dedicated aerodynamic probe calibration facility which uses a free jet in which the probe is traversed has been described. In this facility the probe incidence and Mach number are systematically varied to generate aerodynamic calibrations. Expanding air from a main reservoir tank into a flow nozzle has been a viable method for probe calibration. An example of a three-dimensional aerodynamic probe calibrated at engine representative Mach and Reynolds numbers was presented. Flow measurements with this kind of probe show the versatility of these wide bandwidth aerodynamic probes.

ACKNOWLEDGEMENTS

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