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Development of a New High-Speed Multi-Stage Compressor Facility; Experimental Set Up.

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ABSTRACT

The paper is based on the development and experimental investigation of a new European high-speed research compressor located at Cranfield University. The test facility is designed for multi-stage investigations of highly loaded core compressor stages representative of those found within modern gas turbines. The research was carried out with funding from the European Commission's 5th Framework Programme.

The paper will feature a unique 7 probe assembly and traverse mechanism that has been developed, control software has been written to give a fully automated measurement system which has enabled area traversing of the compressor between each blade row. A small 4-hole probe has been designed and used to take 3 dimensional steady state pneumatic measurements. The first experimental data presented for the datum test comprises of conventionally stacked 2D rotor and stator blades, this will act as a benchmark for a new advanced 3D compressor blade design.

INTRODUCTION

The design of modern compressors is largely driven by the commercial desire to reduce both weight and cost. This has led to the aim of increasing both efficiency and overall pressure ratio of the compressor through reduced parts count. This can be achieved either through a reduction in the number of stages or through the use of fewer blades per stage. The corresponding compressor stages are characterised by high aerodynamic loadings, which lead to complex three-dimensional flow phenomena. The utilisation of advanced 3D compressor blading to address these complex flow structures is now becoming more common place in modern compressor design. However, these advanced blade designs are typically obtained using multi-stage Computational Fluid Dynamics (CFD) prediction methods. There is currently a paucity of experimental data suitable for validating these codes at realistic operating conditions. The paper details the development of a multi-stage facility featuring a 3 stage axial flow compressor with inlet guide vane (IGV). This facility has been used to test a set of datum "conventional" blades at engine representative speeds, the results of which will be used to validate a number of industrial and commercial CFD codes and provide a benchmark for an advanced blade design.

These designs are generally evaluated using a combination of cascade testing and low speed test rigs Howard et al (1993), Lyes and Ginder (1999), Gallimore and Cumpsty (1986). These have the advantages of comparatively low setup, running costs and better instrumentation access, which allows for improved spatial resolution from area traverse measurements. The low speed rig does not fully emulate sub-sonic high-speed blading, found in the rear stages of the HP compressor. For axial compressors the use of low speed test rigs as opposed to full scale high speed test rigs is further complicated by factors such as the unsteady interaction between the rotating and stationary blade rows. For true aerodynamic similarity the blades must have the same scaled surface roughness, Reynolds number and be tested in fluid of the same turbulence intensity.

This paper describes the test rig, the experimental set up, the detailed steady state instrumentation and overall compressor performance. A further paper will describe the results through the compressor at two different operating conditions. These include mach numbers, flow angles and detailed secondary flows.

The purpose of the programme was to adequately measure the flow within a high-speed compressor, to provide comparisons with CFD predictions. Sieverding et al (2000) provides a useful summary of flow measurement techniques throughout a turbomachinery. Prato et al (1998) and Suryavamshi (1998) used a variety of measuring techniques. Total pressure probe for stagnation pressure, aspirating probe for temperature and a hot film probe for velocity data. This built up a composite flow field description of the steady and unsteady flow downstream of the second stator of a 3-stage axial flow compressor.

Vikatos et al (1998) conducted three dimensional flow measurements downstream of a low speed axial compressor rotor. They employed a multi hole pneumatic cobra probe. However the conventional five hole probe consisting of four equispaced holes distributed around a central hole was replaced by a 4 hole probe (3 holes equispaced around a central hole). From this a set of calibration curves are defined which are used to determine yaw, pitch angles, stagnation and static pressures. From these flow parameters the relative axial, radial and tangential flow velocities are calculated using an interpolation algorithm and an iterative loop.

Due to the five hole probes accumulating redundant information four hole probes have become more common for three dimensional flow measurements only four independent variables need to be measured, total and static pressures, yaw and pitch angles. Therefore, a four-hole probe is sufficient as it yields four pieces of information.

COMPRESSOR SPECIFICATION

The datum build for the new test facility for the experimental investigation of high-speed multi-stage axial flow compressors comprises of conventionally stacked 2D rotor and stator blades.
The Specifications of the research compressor are given below. These values are taken from the design data at an overall pressure ratio of 2.4, Mass flow of 10.6 kg/s and a Speed of 9,300 rpm.

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Table 1 Compressor Specification.

Parameter	Stage 1		Stage 2		Stage 3	
	Rotor	Stator	Rotor	Stator	Rotor	Stator
Va/U	0.722	-	0.723		0.736	
H/U^2	0.540	-	0.589	-	0.452	-
DF	0.480	0.460	0.480	0.474	0.465	0.468
Pitch/Chord	0.600	0.571	0.550	0.585	0.700	0.568
No of Blades	71	91	89	107	85	116
Hub/Tip ratio	0.85	0.85	0.88	0.88	0.91	0.91
Re x 10^5	5.82	4.78	6.16	5.03	6.04	4.91
Casing ∅	525	525	525	525	525	525

High Speed Research Compressor Configuration

The configuration of the test rig is described below. The location of this hardware on the test rig is shown as balloons in Plate 3 to Plate 5 in the plates section.

1. Inlet Bell Mouth, sometimes termed a flare; this ensures a smooth inflow with minimum annulus blockage. Designed using standard Rolls Royce practice (McKenzie Flare). This is used to measure the mass flow.
2. Throttling Gauze is used to drop the inlet pressure to the compressor. This reduces the power required from the drive turbine. This also acts as a debris screen.
3. Settling Gauze. This mesh screen takes any swirl out of the flow ensuring a uniform flow structure into the compressor.
4. Inlet Duct. Allows time for the flow to settle, provides mounting for inlet instrumentation.
5. Bullet. This provides a smooth transition of the flow from the inlet duct into the IGV row. The flow is accelerated to match the flow speed out of an upstream compressor. The compressor has a high hub tip ratio that reproduces the rear stages of a multi stage compressor.
6. Compressor. This is shown with the probe assembly mounted on the framework.
7. Outlet Banjo. Collects the air from the last stator and ducts it up through the ceiling of the test cell.
8. Throttle. A pneumatic controlled butterfly valve that enables the flow to be restricted thereby enabling the compressor pressure ratio to be adjusted.

Instrumentation

The high-speed research compressor uses pressure, temperature, speed and torque measurements to calculate the overall performance. These are arranged as described in the following paragraphs

Inlet Pressure Rakes. A total of 4 rakes with 5 Kiel probes each, giving a total of 20 pressure measurements are used to calculate the total pressure at the inlet. These are arranged at 90° spacing around the compressor intake, starting at top dead centre. The pressure tapings are plumbed into a scani valve system and measured using a Druck 145 pressure transducer with a range of 0-10 psi.

Inlet Temperature Rakes. A total of 4 rakes with 4 K type exposed thermo couples each, giving a total of 16 temperature measurements are used to calculate the inlet temperature. These are arranged at 90° spacing around the compressor intake, starting at 45° to top dead centre, on the same axial plane as the pressure rakes. These are connected to a National Instruments analogue to digital converter.

Wall Statics. Wall static pressure measurements are taken in between each blade row. A total of 4 tappings are arranged at 90° spacing around the compressor casing starting at 20° from top dead centre. The pressure tappings are plumbed into a scani valve system and measured using one of the Druck pressure transducer depending on location.

Outlet Pressure Rakes A total of 4 rakes with 5 Kiel probes each, giving a total of 20 pressure measurements are used to calculate the total pressure downstream of stator 3 (Outlet). These are arranged at 90° spacing around the compressor intake, starting at 10° from top dead centre. The pressure tapings are plumbed into a scani valve system and measured using a Druck 145 pressure transducer with a range of 0-20 psi.

Outlet Temperature Rakes A total of 4 rakes with 3 K type exposed thermo couples each, giving a total of 12 temperature measurements are used to calculate the outlet temperature. These are arranged at 90° spacing downstream of stator 3, starting at 45° to top dead centre, on the same axial plane as the pressure rakes. These are connected to a National Instruments analogue to digital converter.

Torque and Speed. A TF-C torque meter from Industrial Measurements Limited was used to measure the torque between the gearbox and compressor. This consists of a full-bridge strain gauge assembly with built in power supply, amplifier and voltage to frequency converter. The speed is measured using a photo diode speed pick up mounted on the torque meter coupling. This gives a once per revolution pulse from a photoelectric cell.

The area traverse probes are controlled by a stand-alone computer. A software control program makes this completely automated. Results from the probe are displayed real time on the computer screen to check for progress and validity. A complete area traverse downstream of a blade row takes approximately 1.5 hours. At equally spaced time intervals during the traverse measurements, the performance program is used to check the performance point. This data is saved and input into the area traverse measurements.

During the run up and steady state running another computer system carries out a Fast Fourier Transform and modal analysis of the blades using the 32 strain gauges attached at various locations to the rotor blades. These ensure the blade vibrations are in acceptable limits and the operating condition is not at a resonant point for a particular blade.

Another computer system monitors a set of capacitance probes located at three positions around each rotor. These measure the tip clearance between the rotors and the abradable coating. These give an indication of wear and any uneven running.

In addition to the strain gauges and tip clearance probes vibration monitors are mounted at various locations on the test rig such as rear bearing, drive turbine mountings and torque meter. These monitor the vibration levels of the drive turbine, gearbox and mounts.

Compressor Overall Performance

The pressure and temperature instrumentation described above is used to calculate the operating characteristic for the compressor. The operating speed is adjusted with the throttle setting for the Rolls Royce Gnome drive turbine. The pressure ratio hence mass flow is adjusted using the butterfly valve. This is repeated for approximately ten points from fully open to the surge point at the various speed lines shown. This yields the performance map shown in Figure 4.

Operating Conditions

Area traverses were taken downstream of each of the blade rows for two operating conditions both at 9000rpm, termed as peak efficiency and near surge. The peak efficiency condition is defined as a corrected mass flow of 10.2 kg/s at a pressure ratio of 2.28. The near surge condition defined as a corrected mass flow of 9.5kg/s at a pressure ratio of 2.4. This enabled a comparison of the flow structure to be made with an increase in loading on the blades.

These traverses were taken using the four-hole cobra probe as detailed below. The position of the probe was measured to the central hole. Due to the left and right ports, being situated below the central port the maximum insertion depth was limited to 4% annulus height. This gave a minimum clearance of 0.2mm.

The probes were traversed across two blade pitches. This ensured all the flow characteristics were captured and the repeatability across the blade passages could be checked. The radial start location for each probe was chosen as an arbitrary point. This point was maintained for each probe traverse. In this way, any influence of an upstream blade row on the downstream row could be checked. For instance, the blade wakes and tip leakages etc are seen to be transported through the compressor influencing the downstream flow.

MECHANICAL PROBE DESIGN

A probe measurement system capable of traversing an area behind each of the seven blade rows was designed. The design of the probe assembly had to have the flexibility to operate with different probes including conventional cobra probes, fast response probes and temperature probes. Due to the size of the axial spacing (min 20mm) and blade height (min 22.4mm) of the research compressor, off the shelf traversing probes were not available. The probe also had to be capable of yawing in both directions and travelling to a minimum depth of 155mm. The mechanical design had to completely enclose the probe when withdrawn, as this would protect the delicate probes during transit. Positional accuracy and repeatability was paramount whilst keeping the design cost effective. The design used seven very similar probe assemblies, as this would take advantage of economies of scale. Wherever possible the author used industry standard parts as this reduces the cost and timescales, this also provides for a quick replacement should any part need changing.

The single probe assembly provides linear motion to allow the various designs of probes to be inserted and withdrawn from the flow. A shuttle is constrained to run up and down the inside of a tube. Electrical and mechanical stops are provided for safety and positional control.

The shuttle is made of bronze to provide a low friction coefficient as it slides up and down the tube. This outside diameter of the bronze shuttle is matched to the inside diameter of the tube to provide the minimum clearance whilst allowing a smooth movement. The stepper motor is connected to the shuttle via a 2mm/rev lead screw, by using a 1.8^o stepper motor this enables a linear motion of 0.01mm per step. This motion is controlled with an anti-backlash nut that consists of two nylon nuts held apart by a helical spring under compression. The leadscrew is constrained at the bottom by a machined transition fit with a radial bearing and at the top by a controlled diameter on the stepper motor mounting flange. This leadscrew is attached to the stepper motor by a coupling and held in place by two setscrews.

At the top and bottom of the tube are two limit switches. These are there as travel limits electronically stopping the stepper motor. The micro switches are wired up normally closed such that if a connector breaks or a power failure to the limit switches occurs then the stepper motor will not move. The top limit switch is also used as the homing switch. Over travel of the probe would result in the probe being driven into the rotating hub, which could result in a catastrophic failure of the compressor.

The probes are inserted through the shuttle and held in place by two dowel pins and two screws. This provides a positive location whilst maintaining the flexibility to mount different types of probes in each assembly. The design of the wind tunnel required that the probes be calibrated at 90^o to their orientation on the test rig. Therefore, there are two sets of locating holes for each probe. The nominal flow angles of 15^o and 45^o for the stators and rotors respectively were known from the design data. The discs were designed such that the probes would be in line with the flow on the wind tunnel when the yaw motor was in its nominal zero position. The probes would then be unscrewed and placed over the other set of locating pin holes to give 15^o and 45^o on the test rig when the yaw motor was in the same nominal position.

The complete design is made up of seven individual probe assemblies. Due to the limited axial spacing of the probes, they could not be individually yawed. Instead, all the probes are mechanically linked via a pulley and gearbox arrangement to another stepper motor. The gearbox is used to step down the motor from 25 revolutions to 1 revolution. This not only provides enough power and resistance to over run but also increases the yaw accuracy. The gearbox is linked to the first probe using a HTD timing belt. The pulley sizes were chosen to give enough room to machine the large one down to provide enough clearance whilst achieving an interference fit with the outside diameter of the first probe. The spacing between the probes was fixed by the test rig geometry i.e. mid passage between rows. The probes had to be very carefully designed to achieve the maximum amount of yaw angle before any clashing of parts occurred. The yaw angle achieved was +29^o, -27^o, which exceeded the necessary calibration range of ± 20^o.

Each probe is connected to the next one, but one, along on opposite sides using alternating male and female rod end bearings (Fig.1). The rod end bearings are held in place using shoulder bolts, these have precision ground outside diameters that match the inside diameters of the shoulder bolts. This provides a flexible joint with the minimum of backlash. The three rotor probes are linked to the four stator probes in a similar fashion. In this way all probes move at the same time, the motion of which can best be described as a four bar chain arrangement. The angle each probe moves will depend on the distance from centreline of the lever arm. The stack up in tolerances and machining variations will mean this distance from centreline will be different for each probe. This was overcome by directly linking the probes to a rotary potentiometer. This is used to calibrate each probe individually for yaw angle.

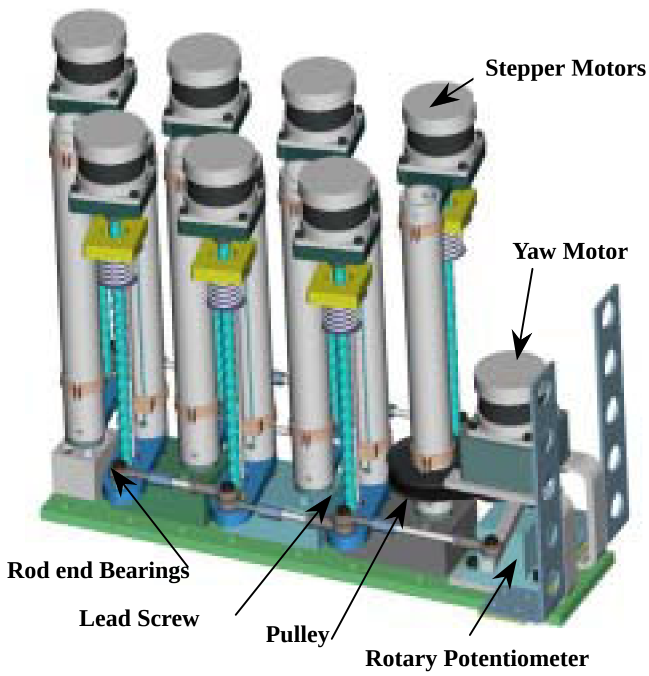

Figure 1. Seven Probe Assembly

Along side the yaw motor are two sets of five electrical connectors. The right hand bank provides the power connection for each of the stepper motors. The left-hand bank provides the connection for the limit switches, rotary potentiometer, Kulite pressure transducers and temperature probes. The two sets were deliberately kept separate from each other to limit the effect of Electro-Magnetic Interference (EMI). This whole assembly was designed so the electrical connectors could be disconnected allowing the probes to be transported as a complete assembly between the calibration facility and the high-speed research compressor facility.

COBRA PROBE DESIGN

The Cobra probe used was a 4-hole probe as shown in Figure 2 and Plate 1 and Plate 2. Four ∅0.43mm stainless steel hypodermics were bent to 90^{o} these were then silver soldered together using a specifically designed fixture. These were then sleeved into another hypodermic of ∅4mm using a small spacer to ensure the four hypodermics were at the back of the external hypodermic. The four smaller hypodermics were left long to allow the finish machining to be carried out. These were then silver soldered into the main stem and the disc detailed above braised on.

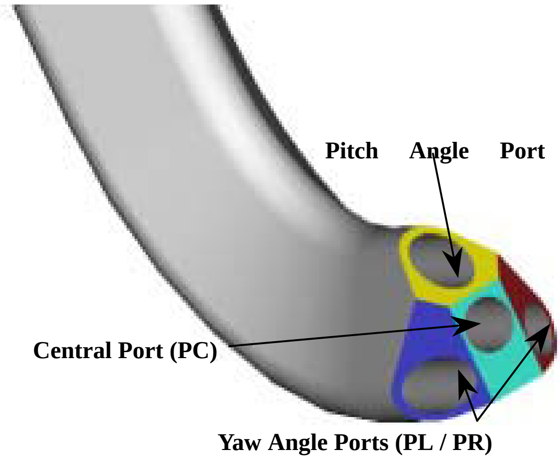

Figure 2. Cobra Probe

Due to the small size of the probe head a new method of machining the facets was required. The conventional method of milling the facets then using a needle file to clean up the facets remains a black art. The facets on these cobra probes were cut using a technique known as Electrical Discharge Machining (EDM) or wire erosion. This technique uses a fine wire that carries a high voltage, this is continually bathed in an electrolytic fluid. The work piece is moved around the wire using a computer-controlled program. This method of machining is commonly used for molds or stamping dies as it has accuracies of five microns and leaves a very hard stable surface. This also has the advantage that the metal is eroded and not torn off, as is the case with traditional methods. The new method created a very symmetrical probe with clearly defined facets. This is evident by the symmetry about the Y-axis of the calibration data. A solid model of the probe head is shown above for clarity the different facets have been coloured.

COBRA PROBE CALIBRATION

The calibration of the probes was carried out in Cranfield's high-speed wind tunnel. Due to the unique arrangement of the probes, all the probes were mounted on the wind tunnel simultaneously. To facilitate this a new wind tunnel section was designed by the author. Rather than maintaining the existing circular cross section a rectangular cross section, measuring 150mm by 60mm was employed. This would allow different cassettes of blades and struts to be mounted into the flow. The wind tunnel was fabricated from ¾" aluminium and screwed together as this would allow greatest flexibility for future modifications.

To increase the Mach number capabilities of the wind tunnel a diverging nozzle was designed to take the flow from the letterbox section to the round section downstream. This allowed a Mach number of 0.78 to be achieved.

To enable the probes to be traversed across the flow a dynamic seal arrangement was required. The top of the wind tunnel has a groove milled around the measurement slot to provide an O-ring seal between the wind tunnel and carriage plate. The complete probe assembly is mounted on the carriage, which in turn is suspended on eight radial bearings. Four of the bearings are constrained to move in only one direction by the use of a V track, whilst the other four can float across a standard flat track. Both sets of bottom bearings are eccentric, which provide a clamping force with the top set. In this arrangement, the carriage plate is held parallel with the wind tunnel, which is necessary to maintain the O-ring seal. Both tracks are mounted on an external extruded aluminium framework. This framework holds the complete assembly against the forces created by the negative relative pressure in the wind tunnel.

Two Chell blocks made by Pressure Systems (Model Number 9010) are used for pressure measurement of the cobra probes; both have 16 channels. The first is capable of reading a maximum pressure of 30psi gauge the second of 45psi gauge both have an accuracy of 0.08% FSR.

The control software was written to enable the yaw angle calibration of each probe to be carried out automatically. Using this procedure each Mach number took 15 minutes to complete.

The wind tunnel mach numbers obtained whilst calibrating the probes was calculated from the static and total pressures using the following equation:

$$M = \left[\left[\left(\frac{Pt}{Ps}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] x \left(\frac{2}{\gamma-1}\right)\right]^{\frac{1}{2}} \qquad (1)$$

The static pressure (Ps) is taken as the average of the two wall static's mounted either side of the wind tunnel on the same measurement plane as the probe half way up the tunnel. The total pressure (Pt) is taken from a Pitot Static probe mounted through the sidewall of the tunnel such that the head of the Pitot Probe is in the same measurement plane as the cobra probe but offset to the left by 25mm.

The pressures are obtained directly from the Chell blocks, with an accuracy of 0.08% FSR for the 30psi Chell block used this corresponds to a Mach number accuracy of ± 0.015.

Yaw Calibration

A computer controlled calibration program was used for the yaw calibration. This enables each probe to be calibrated automatically. The wind tunnel flow is adjusted to give a Mach number of 0.2. The relevant probe is selected; the linear actuator then moves the probe to the correct location. Once at the correct location the probe is driven down to a position in the centre of the wind tunnel, 30mm and 75mm from the top and sides respectively. The probe is then yawed through a –20^{o} to +20^{o} profile in 1^{o} increments. Four readings from the Chell blocks are taken at each location then averaged. This corresponds to a total number of individual pressure measurements of 128 at each location. The results are written as a data file as well as being written directly to an Excel template. This builds up a calibration profile The Mach number is then increased by 0.1 and the procedure repeated until the maximum calibrated Mach number of 0.78 is achieved. The spreadsheets for each Mach number are combined to yield a set of seven curves that are overlaid to give the complete calibration set for that particular probe.

The spreadsheet contains the following formulae to non-dimensionalise the data into coefficients.

$$C_{yaw} = \frac{P_L - P_R}{P_C - P_{AV}} \qquad (2)$$

$$C_{pitch} = \frac{P_A - ((P_L + P_R)/2)}{P_C - P_{AV}} \qquad (3)$$

$$C_{Pt} = \frac{P_t - P_C}{P_C - P_{AV}} \qquad (4)$$

Where:

$P_{AV} = (P_A + P_L + P_R)/3$

Ps is the average of the two wall static's.

Pt is the total pressure taken from the pitot probe.

Pitch Calibration

The probes were calibrated for pitch using a different wind tunnel section. This enables the probe to be calibrated at 10, 5, 2,1 degrees in both the positive and negative directions. Due to the different set up the probes could not be mounted as a complete assembly. Instead, each probe was mounted on a vernier and clamped in position. This enabled the probe to be inserted into the wind tunnel. The vernier is bolted to a rotary table that allows the probe to be yawed as well as pitched.

TEST RIG FRAMEWORK

A framework is mounted outside the compressor; this carries the probe assembly and Chell blocks. The framework consists of a series of extruded aluminium strips bolted to the pedestal blocks on the test rig. There are four pedestal blocks per traverse ring. These traverse rings sit around the rotors. Mounted between the stator rings are four guide blocks these have eccentric bearings that run in a V track cut into the traverse ring. In this manner the whole framework, probes and traverse rings are supported on a total of 32 guide wheels. An electro thrust cylinder provides radial movement of this framework. This supplies a force of up to 600N with an accuracy of 0.0036^{o} per step. The concern with the design of the framework was that it would create twist on the compressor making the traverse rings oval. This would cause the rotors to rub or cause catastrophic failure of the compressor.

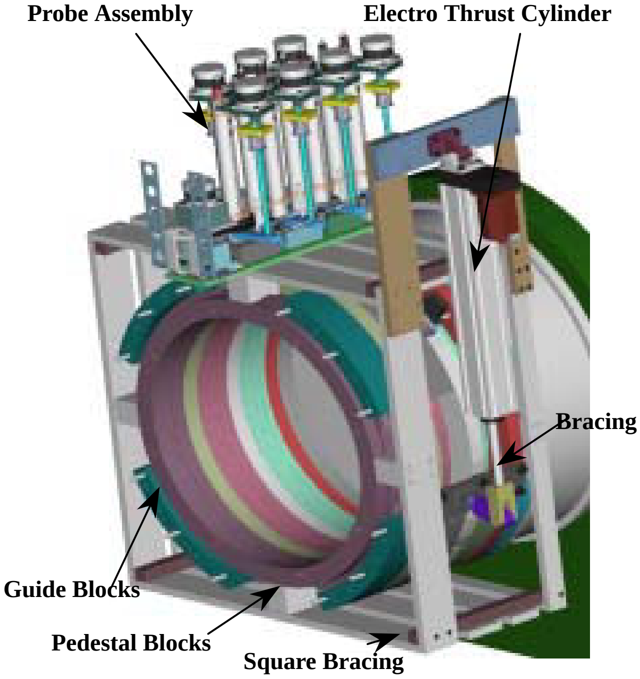

Figure 3. Test Rig Framework and Linear Actuator

The possibility of this was minimised by bracing the connection of the linear actuator across all three stationary rings. The current to the linear actuator was tuned to give the minimum amount of force necessary to drive the framework. This ensured that if anything jammed the movement then the linear actuator would stall prior to doing any damage. The maximum achievable radial movement with the actuator is 30^{o}. This was restricted to 15^{o} during our testing due to other instrumentation on the test rig.

There are three micro switches mounted on the test rig. Two for CW and CCW travel limits and the third as a homing switch. The homing function works by driving the linear actuator in the CCW direction until the homing switch is activated. The linear actuator then stops, reverses direction and travels in the CW direction until the homing switch is de-activated. This method takes up any backlash within the system. This home position was used for all the area traverses.

ELECTRICAL HARDWARE

As with the hardware for the probes off the shelf electronics for the stepper motor drives have been used. Wherever possible commonality with existing equipment used on other facilities within Cranfield has been adopted

The stepper motors are controlled in pairs from a control board. The first one of these is linked to a PC via an RS232 serial link, the remaining boards are all daisy chained off the first. The motors are driven in units of steps using an EPROM software language.

A Parker OEM 750X motor drive board was used for the linear actuator. The board allows feedback from a rotary encoder, stall detection, ramped starts and stops, homing, power control. This board is programmed using a different program language called Parker X. This is connected to an independent RS232 serial link on the PC.

All the cables used in the construction of the electrical layout were braided wire shielded. One end of this was electrically linked to an earth point at the control board power supply. The other end was left unconnected to ensure there was no earth loops within the system. The shielding was used to protect the low power circuits against EMI and electrical noise.

GRID SPACING ON RIG

The number of measurement points taken over an area traverse is a compromise between achieving the spatial resolution to pick up the flow detail and the time taken. To ensure the whole pressure profile was captured during the area traverses the grid density or number of points per pitch was investigated. Probe 5 downstream of stator 2 was inserted down to 50% annulus height. The probe was traversed at a measurement point spacing of 16, 30 and 40 points per pitch. The yaw coefficient was used as the reference as this shows a rapid transient as the probe passes through the stator wake. The 16 points over 2 pitches does pick up the flow transient however the extremes could be lost depending on the location of the wake. The 40 points per pitch showed very little variation to the pressure profile and would have increased the time from 1.5 hours to 2 hours. The value of 30 points per pitch, was chosen as the best compromise.

The traverse gave a grid density of 61 points over two pitches at varying percentage annulus heights totalling 24 points radially. This gives a total number of 1464 data points over an area of 2 blade pitches. The percentage heights were varied from 100% down to 97% then down to 4% annulus heights in 5% steps these intervals were chosen to give greatest clarity to the areas associated with the greatest loss. The value of 61 points over 2 pitches gives a point separation varying between the casing and the hub as shown in the following table. The spatial resolution from the probe is made up from the separation between the ports on the probe which is 0.44mm and the inside diameter of the hypodermic which is 0.4mm reducing the distance between the points below these values will not lead to any further increase in data capture.

Table 2 Probe Measurement Point Spacing.

Probe Number	Distance Between Points at Casing (mm)	Distance Between Points at Hub (mm)
1	1.483	1.266
2	0.773	0.673
3	0.604	0.535
4	0.618	0.558
5	0.513	0.469
6	0.618	0.568
7	0.477	0.438

PROCESSING COBRA PROBE DATA

The results from the test rig were post processed using a program written by the author. The program uses two Excel Spreadsheets, the first is the Excel spreadsheet created during the calibration procedure. The second Excel sheet is created during rig running from the Multiple Probe Acquisition Software program.

The computer program uses the actual pressure measurements taken during the running. The yaw coefficient obtained from the rig running is used to ascertain the yaw angle from the calibration data. This initially is carried out at an assumed mach number of 0.4 as the actual Mach number is not yet known. The variation in yaw angle with Mach number is generally very small but re-calculating the yaw angle after the Mach number is known takes into account any variations at the extremes of flow angle.

The Mach number is obtained from the Pc over P average from rig and Pc over P average vs. Mach number graph from the calibration. This shows the variation of the pressure on the central port with changes in flow angle and an increasing mach number. There is very little change in Pc/Pavg with yaw angle therefore the coarse yaw angle calculated to 1 decimal place above will not lead to any error in the mach number calculation.

The value of 1-Cp0 vs. Yaw Angle for the correct Mach number is used to obtain a value of 1-Cpo. Given

$$\mathrm{Cpo} = \frac{\mathrm{Pt} - \mathrm{Pc}}{\mathrm{Pc} - \mathrm{Pavg}} \tag{5}$$

1-Cpo is an inverted loss bucket. This uses the value of total pressure taken from a pitot probe mounted in the wind tunnel during calibration to calculate how much of the total pressure the central port of the probe is recovering. This is used as a recovery factor, in this way although the probe may not be exactly in line with the flow the application of the recovery factor will yield the correct value of Pt for that measurement location.

All the processed values are obtained by assuming there is a straight line connecting each calibration point. This is considered an accurate assessment due to the linearity of the calibration graphs. The actual values are obtained by interpolating the relevant calibration points above and below the rig value then calculating the corresponding value for the rig values.

Mapping Yaw Angle Ports

The calibration of the probes is carried out in a steady uniform flow. However, as the probe is traversed across a blade passage the left and right hand ports referred to as PL and PR respectively are subjected to different pressures (see Figure 2 for port definitions). This is due to the distance between the ports. Although this value is only small (0.44mm nominally between the central port and the left and right ports) this gives an apparent rapid flow angle excursion as the probe is traversed through a wake. This fluctuation is due to the fact that PL enters the wake (Hence reduced Pressure) prior to PR causing the numerator of the yaw coefficient to become negative. As the probe passes through the wake PL enters the free stream (increased pressure) as PR is still in the wake causing the numerator to become positive. When processed this corresponds to an unreal rapid change in flow angle across the wake. The solution was to map the individual results from the left and right ports onto the same location as the central port.

A program was written in Visual Basic 5.0 that calculated the location of the central hole in Cartesian coordinates. The X value offset of the left and right ports in relation to the central port was then calculated. The pressure value of the Left and Right Ports when at the same location as the central port was then calculated by interpolation of the graphs relevant to that particular port.

Originally, the offset was taken as the geometric difference between the ports (0.44mm) however, this value did not map the two graphs together. This offset value was increased until the two graphs of the left and right ports overlapped each other directly beneath the graph of the central port. This figure was found to be between 0.6mm and 0.74mm. The author believes this is due to small manufacturing variations between different probes, the presence of the probe in the flow and the interaction of the probe with the flow. There will be a boundary layer around the probe, which in effect increases the wetted area of the probe.

Once the new values for the left and right ports are known, the mapped yaw coefficient is calculated. This new yaw coefficient is used in the post processing to calculate the flow angle. When this is applied to the traverse data at all the radial heights taken, the large flow fluctuation evident by closely packed contour lines disappear. Figure 5 shows a contour plot of yaw angle prior to the mapping procedure being used, this can be compared to Figure 6, which is the same data set after mapping. The figures clearly show the effectiveness of the mapping procedure. The apparent rapid flow angle excursion as the probe is traversed through a wake evident by the closely packed contour lines has disappeared in Figure 6. The magnitude of overturning and underturning has also been reduced.

Mapping Ports For Pitch

The spacing of the ports when measuring pitch angle is very significant. There is a large radial pressure gradient this leads to a large difference in pressure on the individual ports. The location of the central port is taken as the measurement point, i.e. when the centre of PC is at the casing this is considered to be 100% annulus height. This means that the top pitch hole (PA) does not see any flow until approximately 97% annulus height. Due to the pressure gradient the pitch hole sees a lower pressure, particularly at the end walls this will lead to a very positive pitch angle. The solution was to map the ports radially to the position of the central port. The values for the left and right ports were also mapped radially in a similar way.

At the final sweep i.e. 4% annulus height the value for the top port cannot be mapped down, as the value is not known. This is taken to be the same value as at 5%, this only gives a slight error, as there is very little pressure gradient between 4 and 5 %.

Once all the ports have been successfully mapped a new Pitch Coefficient is calculated. This is substituted into the Excel results worksheet and used to calculate the pitch angle.

Processing Pitch Values

The values for pitch angle were processed in a slightly different manner to the yaw angles. There was only a limited number of pitch angles available on the wind tunnel therefore taking a value between each point when the values were up to 5^{o} apart could lead to errors. The maximum pitch available on the wind tunnel was $\pm10^{o}$ by using a straight-line fit equation this could be extrapolated up to $\pm20^{o}$. The pitch coefficients were converted into pitch angles by using a unique equation for each probe. This equation was calculated from the Excel charts created during the calibration procedure.

Measurement Accuracy

The Chell block accuracy is quoted as ±0.08% FSR this was checked with a calibrated Druck pressure transducer and found to be within ±0.04% FSR. The error is still taken as ±0.08% FSR as this is considered a worse case value and will be maintained up to a year after manufacturers calibration procedure. The Chell blocks have individual pressure transducers in each port these have temperature compensation modules wired in to account for variations in ambient temperature. Prior to any pressure measurements being taken the Chell blocks were powered up for a minimum of half an hour to ensure the inbuilt electronics had reached a stable operating temperature. The greatest source of error would be that of zero offset. The Chell block control software has the code to enable a re-zero calibration procedure to be carried out. This was carried out prior to any running when the ports are at ambient conditions.

During the calibration and rig running the same pressure ports were used, this ensured that any non-linearity between pressure transducers was eliminated.

In addition to the error created by the pressure measurements there is also the error created from the rotary potentiometer feedback loop. This error although small (a maximum of ± 0.144 degrees) is accounted for as an angle offset in the area traverse Excel spreadsheet. The rotary potentiometer feedback loop and this angle offset only leaves the accuracy of the voltage measurement carried out by the ADC card this is negligible and equates to ± 0.072 degrees.

The author considers an error of ± 0.3° for yaw angle and ±0.7° for pitch angle an adequate evaluation for the stack up of inaccuracies.

The total pressure measurements are taken directly from the central port therefore this value is not derived from calibration data. This value for total pressure is divided by a recovery factor that is derived from a comparison with an industry standard pitot probe during the calibration. The author believes a value taken from the accuracy of the Chell blocks of ± 0.036psi is correct assessment of the total pressure measurement.

CONCLUSIONS

The size of the probe was of particular concern as this was a compromise with what was manufacturable yet small enough to adequately pick up the flow structure. The EDM machining method employed gives an extremely well defined probe head that gives a clear calibration profile.

The procedure used to map the ports was so effective that the left and right ports could have been spaced further apart on the same centreline as the central port. This would allow the central hole to be traversed closer to the hub boundary layer.

The measurement technique chosen, the design of the hardware and software control has yielded some very detailed results within a high-speed environment. The unique data set has enabled various CFD codes to be validated.

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FIGURES

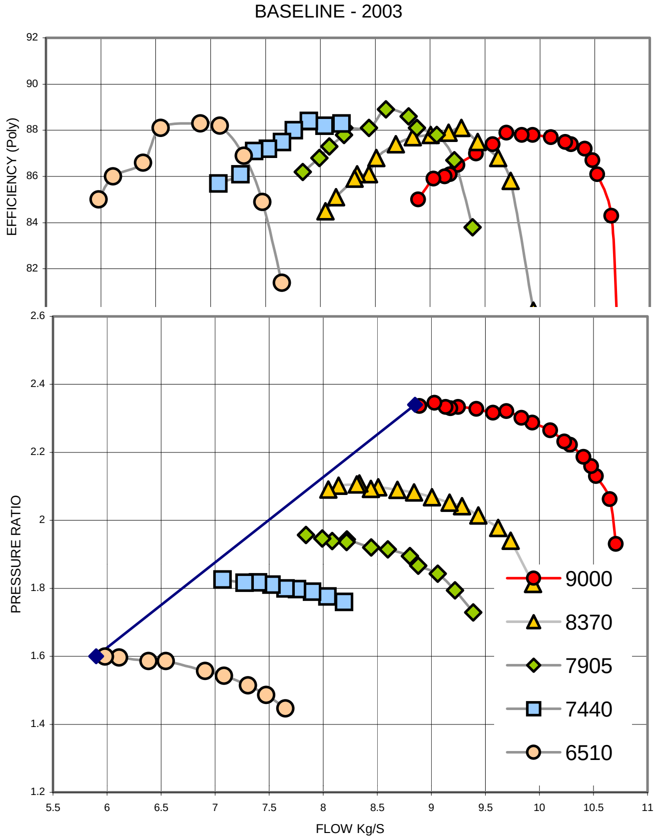

Figure 4 Compressor Chic

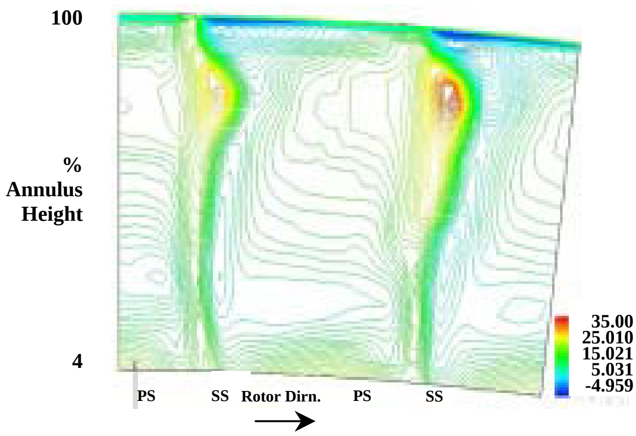

Figure 5
Yaw Angle Downstream of Stator 2 Near Surge Prior to Mapping

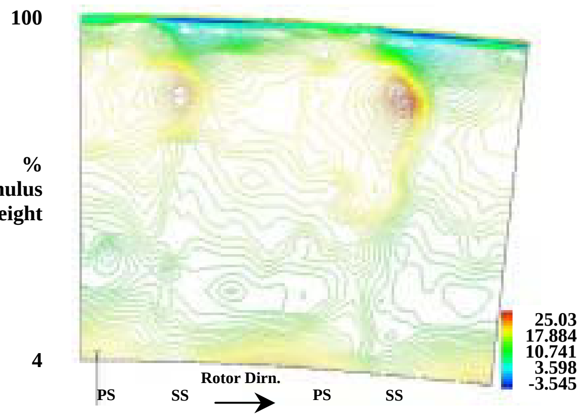

Figure 6
Yaw Angle Downstream of Stator 2 Near After Prior to Mapping

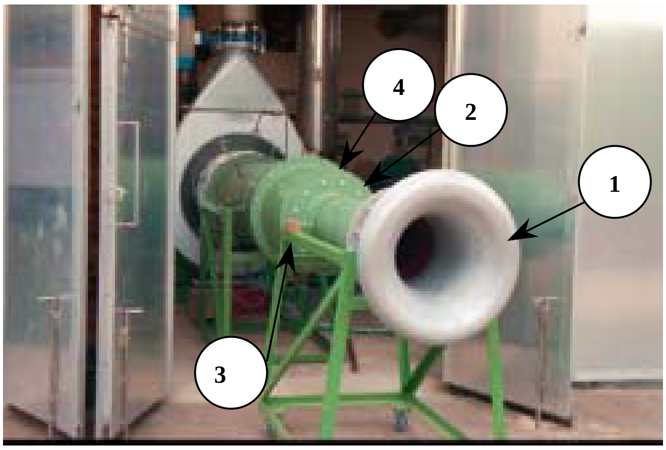

Plate 3
Front end of Facility

PLATES

Plate 1
Cobra Probe Head

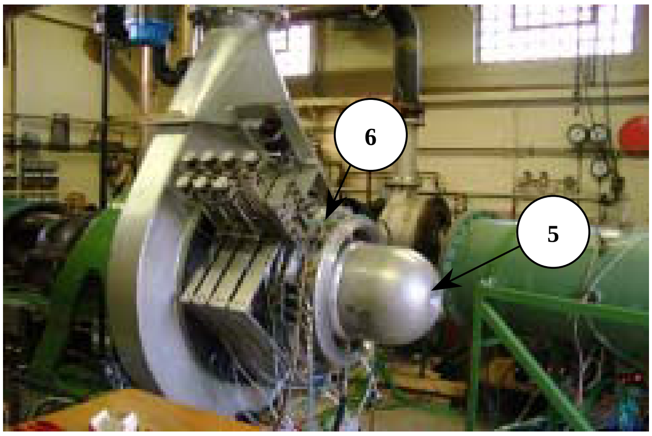

Plate 4
Inside Facility front Duct Removed

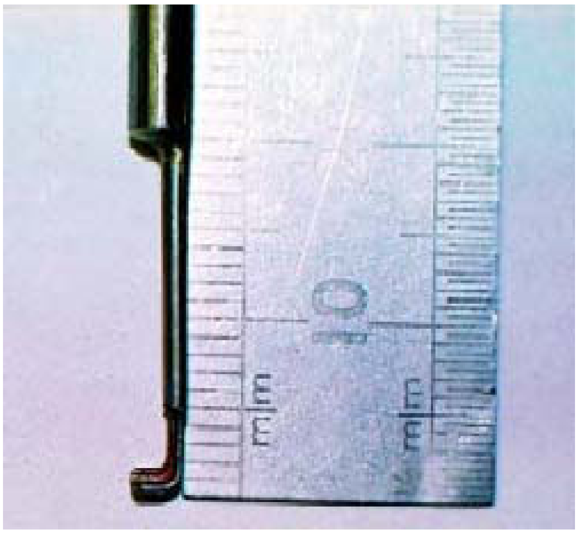

Plate 2
Side View of Cobra Probe, Showing Size

Plate 5
Compressor showing Outlet Banjo and Throttle Valve