Tech Memo
AERO 2222

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AERO 2222

DEFENCE RESEARCH AGENCY
AEROSPACE DIVISION

Technical Memorandum

September 1991

Introduction of Electronic Pressure Scanning at the Royal Aerospace Establishment

by

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RAE, Bedford, Bedfordshire

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CONDITIONS OF RELEASE

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DEFENCE RESEARCH AGENCY

Aerospace Division
RAE Bedford

Technical Memorandum Aero 2222

Received for printing Oct 1991

INTRODUCTION OF ELECTRONIC PRESSURE SCANNING AT THE ROYAL AEROSPACE ESTABLISHMENT

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SUMMARY

An electronic pressure scanning system has been installed at the Royal Aerospace Establishment Bedford (UK) and has been used to provide pressure data in wind tunnel tests on aircraft models. This paper contains the results and conclusions from the laboratory experiments that were undertaken to assess the effectiveness of the system in the wind tunnel environment. The paper also contains a summary of the system performance during model tests in the first six months of tunnel running. It is shown that the system offers considerable savings on pressure data gathering times over mechanical pressure switches previously in use. Error analysis of the data from the system has shown that existing high measurement accuracy has been retained. The paper highlights the advantages and disadvantages of using such a system.

Key words: Electronically Scanned Pressures
Wind Tunnel Instrumentation.

Presented at the 37th International Instrumentation Symposium of the Instrument Society of America, San Diego, California, 5-9 May 1991.

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INTRODUCTION

Fig 1 shows the 8ft x 8ft High Speed Wind Tunnel at the Royal Aerospace Establishment Bedford. This national research facility has a continuing programme to improve the speed of acquisition and accuracy of measurements.

A detailed analysis of the requirements of tunnel users for the measurement of steady pressure was undertaken in 1988. This concluded that an electronic pressure scanning system could offer an accuracy the same as or better than that of the mechanical pressure switch system it would replace and have a faster data acquisition rate.

In early 1989 an Electronic Pressure Scanning (ESP) system capable of handling over 1,000 pressure ports simultaneously and passing fully corrected pressure data direct to the host computer was procured. The selected system consists of seven different units configured for use in the 8ft x 8ft Tunnel as shown in Fig 2. Appendix A contains a brief description of the system components. The system uses semiconductor transducers of the piezo-resistive type, microprocessors on a VME bus running the C programming language, servo controlled pressure sources and pneumatic valves.

The system was evaluated in the laboratory before being installed in the tunnel The results of various experiments carried out to assess system performance and the experience gained from using the system in the tunnel are described. The information presented includes the evaluation of basic accuracy, hysteresis, stability, temperature effects, noise, 'carry-over' (defined later) and sampling errors as well as a description of the methods employed to produce the most reliable and accurate results

The paper shows that the system allows the pressure transducers to be transfer standards between the model and the secondary standard in the calibration unit. The system offers considerable savings in pressure data gathering times over previous systems while retaining high accuracy data output.

LABORATORY EVALUATION OF THE SYSTEM

CALIBRATING THE PRESSURE CALIBRATION UNIT

For these experiments the pressure calibration unit was made to generate absolute pressures covering the whole range of pressures available. The pressure output of the pressure calibration unit was measured against an accurate manometer and found to be in very close agreement, well within the 100 Pa combined error of the two instruments. The results are plotted in Fig 3.

The secondary standard in the calibration unit relies on gas density to make its measurement and is normally supplied calibrated for air. Nitrogen gas was used for this test and in the light of the good correspondence between the pressure calibration unit and manometer, which is a bellows device not sensitive to this effect, we believe that errors are acceptable within the overall accuracy.

CALIBRATING THE PRESSURE SCANNING HEADS

The diagram of the apparatus used in this set of experiments is shown in Fig 4. The pressure scanning heads were attached to the system as they would be in a wind-tunnel model (Fig 2). All the pressure ports were linked into a common reservoir, the pressure in which was controlled by a pressure regulator. The pressures generated by the pressure regulator were also fed to the manometer. The tubing was such that the manometer measured the pressure as close to the pressure scanning heads as possible, minimising the effects of pressure differences along the tubing caused by leaks. Owing to the amount of tubing involved and the uncertainty of the sealing in the various devices attached to the common reservoir, it was impractical to reduce the leaks to less than 3 Pa/s at 135 kPa differential. This was considered acceptable as the time to take the readings was approximately one second.

Several different tests were carried out to assess the ability of the pressure scanning heads to give accurate pressure measurements, each run using an improved technique to increase the accuracy to the maximum possible for the system.

BASIC SCANNING METHOD

In the experiment pressure was applied from -83 kPa d up to the full scale of 135 kPa d in increments of 17 kPa, followed by decrements of the same amount to the starting pressure. At first the settling time was set to a minimum, and pressure readings were taken as soon as the pressure regulator reached the correct pressure. However, the results proved to be too random and the settling time was increased to 5 seconds which appeared to be sufficient for the system Fig 5 shows the output from all 48 transducers when supplied with the pressures It should be noted that:

(a) The graphs show errors compared to the output given by the manometer. The systematic error is ±0.05% FS and there is a scatter of ± 0.025% FS about this

(b) The data have been plotted against time rather than pressure in order that any hysteresis or instability of the transducers can be identified by a lack of symmetry of the response with respect to a vertical line passing through the maximum

EFFECT OF NUMBER OF SAMPLES

Fig 5 shows excessive random noise The cause of this was not investigated but due to the length of the cables used it may have been from pick-up of electrical noise in the very active electrical environment. The manufacturers have, as part of their operating software, the ability to average a pressure data point reading over several samples. A weakness of this system is that one stray data point affects the output, which could be prevented in a more sophisticated system. For this experiment the system was set up to average each data point over a number of samples sufficiently large to obtain the highest accuracy from the system. This technique had the effect of smoothing out the error lines considerably, and assumptions about electrical noise seem to have been justified. Fig 6 shows the output from all 48 transducers when 100 samples are taken at each data point

EFFECT OF TIME

The most notable trend of the results shown in Fig 6 is an increasing error as the run took place. The time for a run to complete was about 10 min. To reduce this error a zero point calibration was carried out, by applying the same pressure to both sides of the transducer diaphragm, directly after every data point was taken. This meant that the system was effectively recalibrated 30 s before the next data point was taken, owing to the time required to generate the pressure. This increased the length of the runs to about 15 min but the diverging errors were effectively controlled and all the data points fell well within the 0.05% of full scale that had been set as the allowable error limit of the system. There now appeared to be very little random error contribution as all of the lines on the graph followed virtually the same path (Fig 7). The line of the graph was still not straight, however, but showed some kind of systematic error and a mirror point about the maximum pressure. Comparison with Fig 3 suggests that the systematic error may be the actual variance of the pressure calibration unit to the manometer. However, the overall errors are acceptable. The typical error is 0.03% and the worst case 0 04% of full scale. It should be noted that the sensors are calibrated over the whole range and that 100 samples are taken per data point.

THE PROBLEMS OF CARRY-OVER

Any measurement system that switches between different input signals must recover from the step change. The transient response to the step will take a finite time to settle within a specified error band. The steady state response may exhibit hysteresis. Carry-over error is the combined result of these two effects The contribution due to hysteresis is determined by system design. The settling time may be varied by changing the rate at which the system switches between different input signals in order to investigate the transient contribution.

Carry-over checks were made by taking every other four pressure ports from a pressure scanning head and venting them to the atmosphere. The pressure on the remaining ports was then stepped from -83 kPa d to 135 kPa d in exactly the same way as the calibration runs. In this mode the system was found to show definite loss of accuracy. It was immediately obvious from studying the outputs that a large carry-over problem existed when using the pressure scanning heads.

Fig 8 shows the effects of carry-over on a pressure scanning head when the pressure is increased. This data was taken using 100 samples per data point and a zero calibration between data points Fig 9 shows the carry-over effects by port number. The error is 0.14% of the pressure step onto the port. The accuracy was increased when parallel address mode was used with four or more pressure scanning heads, instead of sequential mode.

These problems were discussed with the manufacturer who described it as comparable with the kind of problem encountered with pressures in a rotating pressure switch system and suggested two ways around the problem.

(a) Group all similar pressures together on the scanner ports.

(b) Only read the ports that are being used.

However, these suggestions do not address the inherent problem, which needs to be solved. The instruction manual reveals no way to slow down the data rate of the Analogue to Digital Converter (ADC) to investigate the effects on carry-over but the manufacturer has since confirmed that it is possible for them to slow down the rate at which the ADC takes its data, and modification is being contemplated.

INVESTIGATION OF COMMON-MODE EFFECTS

This experiment set out to investigate the common-mode or line pressure effects. The pressure scanning head was rigged so that the same pressure was applied equally to both sides of the pressure transducers. This pressure was then stepped from 17 kPa to 235 kPa in increments of 17 kPa and then down. Two separate experiments were performed:

(a) All 48 ports and the reference port were linked together The calibration port was left vented to the atmosphere and the internal valve was set to the 'run' position.

(b) The calibration port and reference port were linked together. The measurement ports were vented to the atmosphere and the internal valve was set to the 'calibration' position.

Figs 10 and 11 shows the observed errors when the pressure was cycled It is interesting to note that the common-mode pressure errors are not the same for both positions of the valve. This can probably be attributed to the fact that the valve consists of a solid metal block which slides backwards and forwards The valve position may alter the stress loading on the pressure scanning head. It is, however, a cause for concern to observe that the calibration technique is unable to compensate for this effect.

INVESTIGATION OF SUPPLY RAIL VOLTAGE STABILITY

The long-term behaviour of the 5 V DC transducer supply rail was investigated in an attempt to deduce why there was such a noticeable divergence of the transducers with time. Fig 12 shows the apparatus used to read the data. The potential divider allowed the analogue to digital converter to measure changes of more than ± 5 V on the voltage rail, to a resolution better than 0 5 mV.

No data are presented in this paper as the rail was found to be stable to within the 2 5 mV required to achieve 0.05% FS system accuracy. With zero pressure difference applied to a transducer and with a well-balanced Wheatstone bridge the output is zero and so is not dependent on voltage changes in the supply rail. When a pressure difference is applied to a transducer, however, this is not the case and the bridge output will be dependent on the supply rail

Investigation of the transducer response with a variable supply rail confirms that the sensitivity is directly proportional to the supply rail voltage

EFFECTS OF TEMPERATURE

A single 48 way pressure scanning head was placed in an oven that could be controlled over a temperature range of 260 K to 320 K. A ribbon cable made connection with a module test box outside the oven which contained power supplies and a voltmeter with a resolution of 1 part in 10,000. The transducers' bridge excitation was measured by a high-accuracy voltmeter as close to the pressure scanning head as possible. The pressure scanning head was set to the calibration position and a pressure line from the calibration port was taken out of the oven to a controllable pressure supply. The temperature was stepped from 263 K to 313 K in steps of 5 K and allowed to stabilise to within 0.5 K of the desired temperature. At each temperature 3 pressures, 35 kPa A, atmospheric and 173 kPa A were supplied to the head and the raw output voltages were taken for three different transducers. The bridge excitation voltage was also noted at each reading.

Fig 13 shows how the transducer zeros change with temperature. To keep within the desired accuracy, 0.05% FS, the temperature of the module must not change by more than 1.2 K between zero calibrations Figs 14 and 15 show how a transducer's sensitivity varied with temperature for positive and negative pressures. Taking the worst case of slope change the temperature of the modules must not change by more than 2 K between full calibrations These changes pose no problem for tests in the 8ft x 8ft Tunnel where total temperature changes by less than 1 K per hour. Fig 16 shows how the bridge excitation voltage varied during the experiment The change in the bridge excitation is an order of magnitude less than these effects.

COMMISSIONING AND USE OF THE SYSTEM

CONFIGURATION OF THE SYSTEM

The 8ft x 8ft Tunnel is capable of being pressurised from 13 kPa A to 415 kPa A and has operating Mach number ranges of 0.13 to 0.9 and 1.3 to 2.5. The flow experienced in the tunnel generates pressures on the model typically 100 kPa below tunnel static pressure. Scanning heads of 135 kPa d range were chosen for this environment. These are calibrated using a 345 kPa A secondary standard

Fig 2 shows a block diagram of the system configuration The range of tunnel pressures meant that it was not possible to put the pressure calibration unit inside the tunnel shell and so it was put just outside with a 30 m length of 3 mm diameter nylon tubing connecting it to the pressure scanning heads.

The main signal processor is connected to the host computer by an IEEE-488 interface for the efficient transmission of data at high speed. To comply with the specification of the IEEE-488 interface, the processor had to be within 20 m of the main computer. The longer the distance between the pressure regulator in the pressure calibration unit and the pressure scanning head, however, the longer the pneumatic settling times and the more time needed to perform a calibration The solution was to use a remote processor that could contain the pressure calibration unit and be close to the working section The two processors are joined by a RS-232 link capable of working over a distance of 60 m. The data rate is not critical as the pressure calibration unit is a slow device.

The models are rigged with flexible PVC pressure tubes, typically 1 m long and 1 mm in diameter. The tubing is arranged to give adjacent transducers similar pressures to overcome the carry-over problem. The control lines have to be thick wall 1 mm nylon tubing with a 1.5 mm nylon sleeve over the connection to the pressure scanning head to withstand the 830 kPa pressures applied The diameter of the control lines is increased to 3 mm as close as possible to the model to improve the flow.

Two adjacent pressure ports on each pressure scanning head are rigged to receive a tunnel wall hole pressure close to full scale value so that the head can be checked for malfunctions The pressure read by the pressure scanning head is compared to a high accuracy transducer and the user alerted if the difference is greater than a preset error band. This also informs the user when the transducer has drifted outside specification and that calibration is due.

The pressure scanning heads used at RAE Bedford each require 12 wires to operate. This can cause physical congestion, so interface cards that only require 19 conductors for 8 heads are put in the model. These also provide a point close to the heads to regulate the bridge excitation voltage. It has been found that a 10 m ribbon cable can be laid down the sting and joined to the standard system cable without loss of accuracy

For a typical test the transducers are fully calibrated during Mach number changes, which occur about every 30 to 50 minutes, and zero calibrated whenever they go outside specification according to the check described earlier A pneumatic valve system was installed to switch the transducer reference side to atmosphere during the calibration sequence as the tunnel reference is unstable during Mach number changes.

Whilst taking data the transducers are referenced to the tunnel total pressure This means that, for most tests, all the pressures on the model are negative and so the system only has to be calibrated in the negative quadrant. A two-stage calibration is done to save time. This entails a full three point calibration followed by a zero calibration. It has been found that the pressure calibration unit performs best with a slightly positive pressure instead of a zero pressure during the full calibration because of the way its servo valve operates.

The tunnel users are encouraged to take repeat data points so that they can assess the repeatability of the pressure system For each data point 4 seconds are available in which to acquire pressure data allowing 64 samples per port to be averaged for a 1,000 port model. This number of samples is sufficient to reduce the system random noise to less than the systematic errors for data from the surface of a pressure plotted model A mechanical pressure switch would take at least 12 seconds to obtain the same results.

PERFORMANCE OF THE SYSTEM IN THE TUNNEL

The first time the system was used in the 8ft x 8ft Tunnel was during the annual tunnel calibration in the summer of 1990. A 48 way pressure scanning head was connected in parallel to the usual high accuracy measurement system used in the test The tunnel was run at subsonic Mach numbers between 0.42 and 0 85 and Reynolds numbers of 2 and 4 million per foot A total of 60 data points were taken with the system and 32 pressures were measured at each point. The data was compared directly to the data from the usual measurement system. A full calibration of the system was done every half an hour.

Fig 17 shows a histogram of the error distribution of the data taken by the system in this run Data from two of the ports was removed since they were outside calibration range. This underlines the importance of calibration over the whole of the expected pressure range. In general, the data was of a high standard and inside the expected error bounds.

USE OF THE SYSTEM IN MODEL TESTS

The first model in which the system was used had the pressure scanner interface cards outside the model on the end of 14 m long module cables and it was not possible to use the zero calibration due to software problems. This model did not yield good results and the data accuracy was limited to about 170 Pa for smooth flow degrading to 700 Pa in the intake. There were no failures of the pressure measurement system

In the second test the pressure scanner interface cards were inside the model. All calibration options were available and the test was successful. The accuracy was improved to 100 Pa in steady flow conditions Again, there were no failures of the pressure system. This model was previously tested in another tunnel with a different type of electronic pressure scanner. The data was found to be in close agreement with results obtained in the 8ft x 8ft Tunnel.

The third model had the pressure scanner interface cards mounted in a sting pod 2 m from the model which had 96 way pressure scanning heads. These are standard 48 way modules with a pressure switching plate mounted on top to select two sets of 48 inputs. The data accuracy was increased 70 Pa before the need to zero calibrate every 10 min started holding up the test.

In general, the tunnel users have been pleased with the system and the tunnel has been able to increase the number of runs in a day with worthwhile financial savings in tunnel time and power compared with the previous system

CONCLUSIONS

The following conclusions may be drawn from our experiments:

(1) Apart from carry-over problems, the system provides an accurate and viable way of reading large amounts of data from multiple pressure ports.

(2) The system is capable of measuring pressures from 17 kPa to 235 kPa absolute within 0.05% of the transducer full scale. This is within the required specification.

(3) For the accuracy to maintained within specification in the environment of the 8ft x 8ft Tunnel, where the temperature changes typically 1 K per hour, the system should be zero calibrated by applying the same pressure to both sides of the transducers every 10 to 20 min. Ideally the system should be zero calibrated before every data point. The system should be fully calibrated by applying known pressures covering the full measurement range every 30 to 50 min.

(4) Until a means to slow down the data rate of the analogue to digital converter is provided all similar pressures should be grouped together on the scanner ports to minimise carry-over errors.

(5) Common-mode effects are not a serious source of error over the pressure range of the 8ft x 8ft Tunnel It is, however, a cause of continuing concern that the common mode errors are not the same for the 'run' and 'calibration' position of the valve, indicating that the calibration technique is unable to compensate fully for this effect.

The introduction of electronic pressure scanning into the 8ft x 8ft Tunnel has allowed accurate pressure data to be taken in one-third the time required when using mechanical pressure switches The system has already saved many hours of tunnel running time and reduced the cost per data point

APPENDIX A SYSTEM DESCRIPTION

The system consists of pressure scanning heads, a Scanner Digitiser Unit (SDU), a Pressure Calibration Unit (PCU) and the associated electronics.

PRESSURE SCANNING HEADS

The pressure scanning heads contain the transducers that measure the pressures. They are available with varying shape, size, robustness, number of pressure ports and pressure range. They contain analogue multiplexers and an amplifier to select and boost a single signal from the pressure transducers. The pressure scanning heads also contain pneumatically controlled mechanical valves to switch between the calibration and measured pressure. Pressure scanning heads are available with a purge option. In these heads the pressure ports are joined together to a reservoir containing a high pressure and the flow of air cleans the tubing system.

SCANNER DIGITISER UNIT

Groups of eight pressure scanning heads are plugged into interface controller boards (IFC) in the model containing simple voltage regulators for the transducer power supplies. Cables from the IFC's are taken out of the tunnel shell to an expander rack that multiplexes the signals for input to the SDU. The SDU contains a 16 bit binary ADC sampling at 50 kHz.

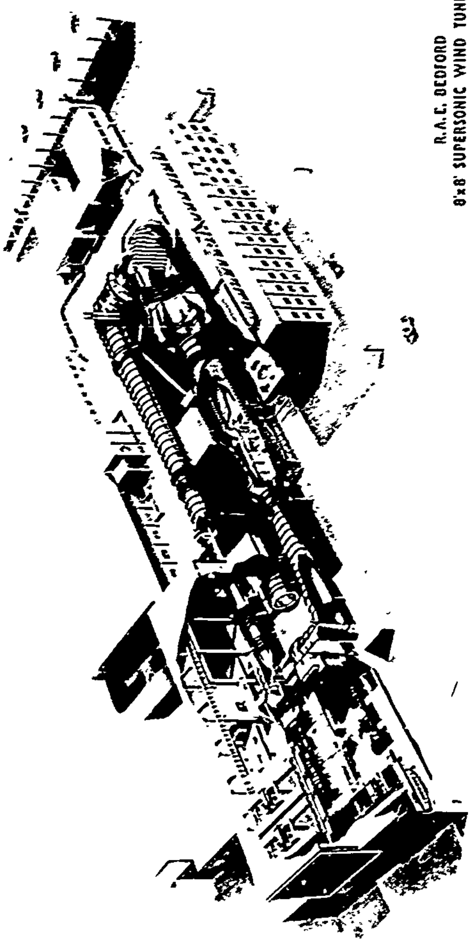
PRESSURE CALIBRATION UNIT

The PCU is capable of generating and measuring a range of pressures under computer control. It also outputs the high pressures that are used to switch the pressure scanners from 'run' mode to 'calibrate' mode. The pressures generated by the PCU are fed to the transducers in the pressure scanning heads so that they can be calibrated against the PCU's high accuracy secondary pressure standard.

ASSOCIATED ELECTRONICS

The system processor holds the main I/O processor for the system, a powerful Motorola microprocessor on a VME bus This computer handles all of the information flow to the host computer through the IEEE-488 bus and between the other components of the system through the VME bus The remote processor is basically a system processor in a minimum form. This device contains a computer of similar power to the system processor and the architecture is also based around the VME bus. The communication between the two processors is by serial RS-232 cable.

Fig 1



R.A.E. BEDFORD
8'x8' SUPERSONIC WIND TUNNEL
GENERAL VIEW

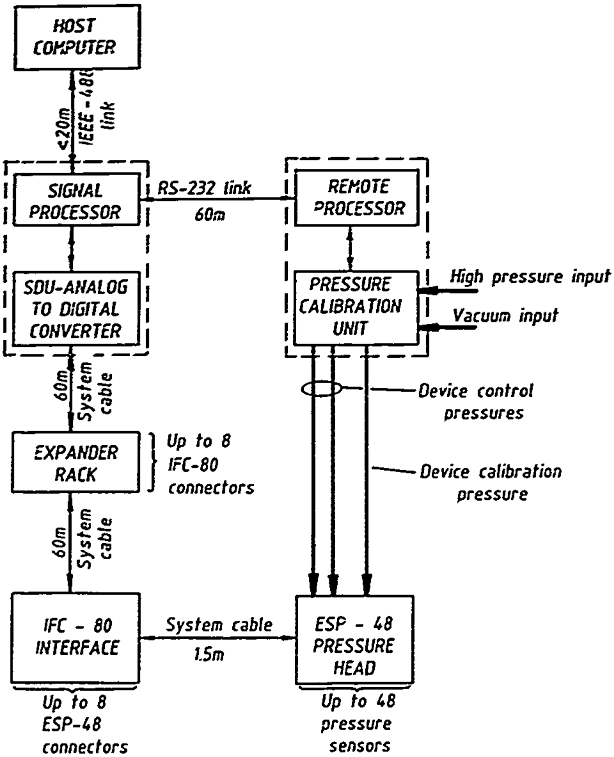
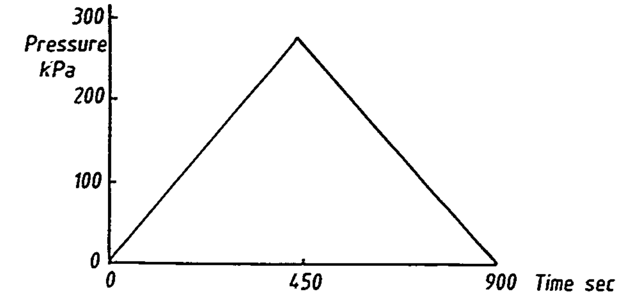
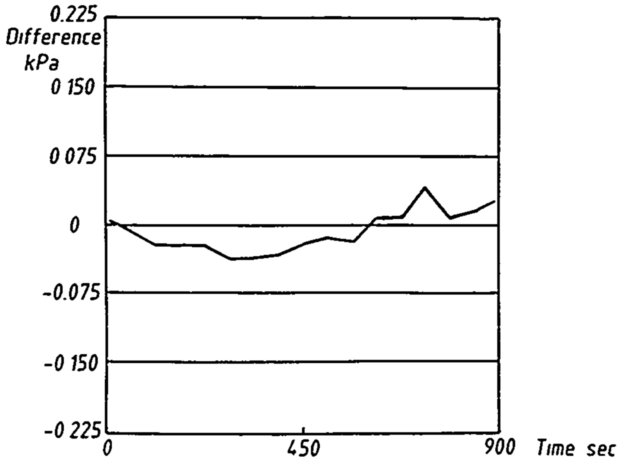


Fig 2 Diagram of the new system at RAE Bedford



a) PCU pressure output applied to manometer



b) Agreement between PCU pressure output and manometer

Fig 3 Calibration of the pressure calibration unit

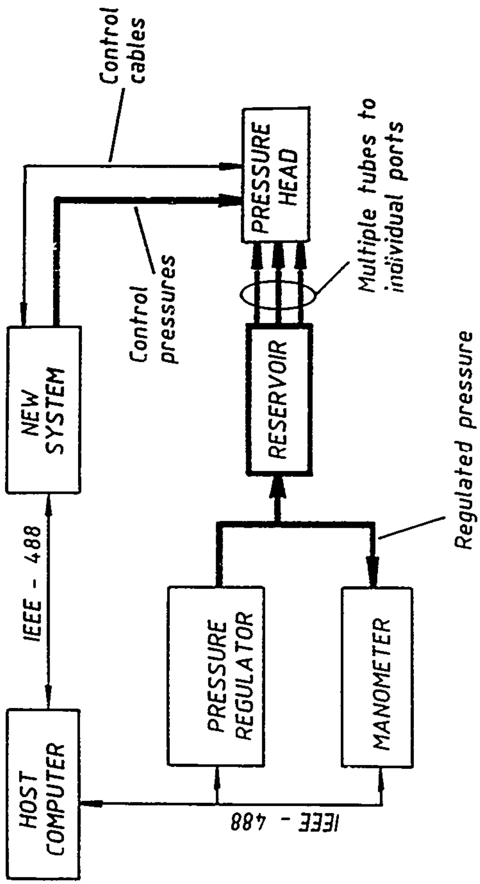
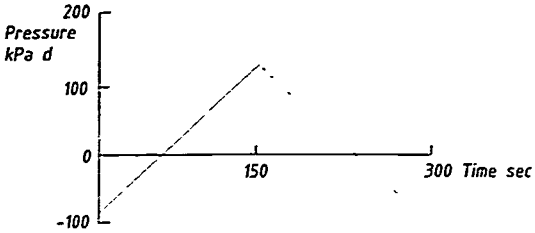
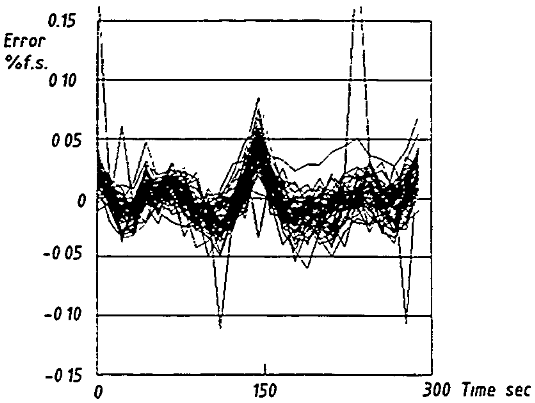


Fig. 4 Diagram of apparatus used to test pressures



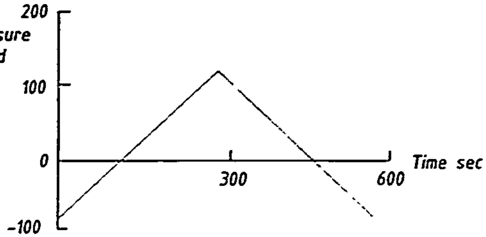
a) Pressure applied to measurement ports, reference to atmosphere



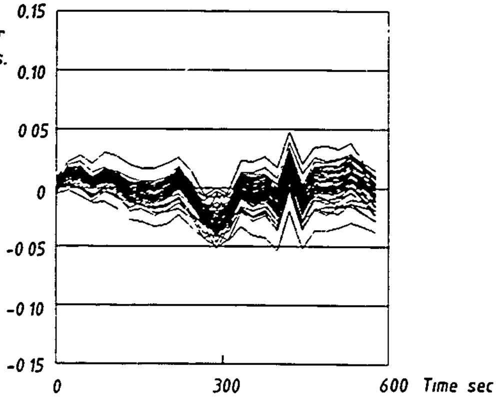
b) Error in response from 48 sensors as % of full scale (135kPa d)

Fig. 5 ESP head with full range calibration

Fig 6a&b

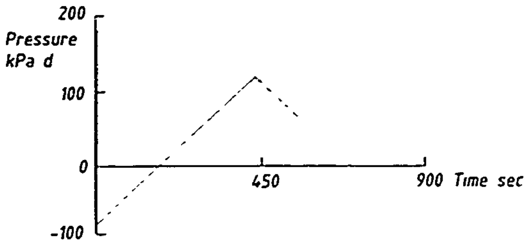


a) Pressure applied to measurement ports, reference to atmosphere

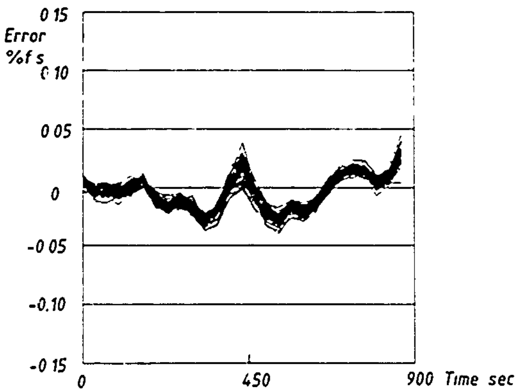


b) Error in response from 48 sensors as a % of full scale

Fig 6 ESP head with 100 samples



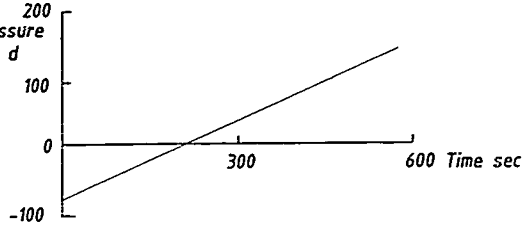
a) Pressure applied to measurement ports, reference to atmosphere



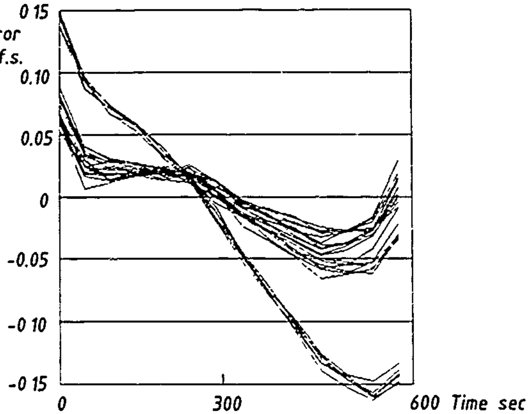
b) Error in response from 48 sensors as a % of full scale (135kPa d)

Fig 7 ESP head with re-zero calibration before each data point

Fig 8a&b

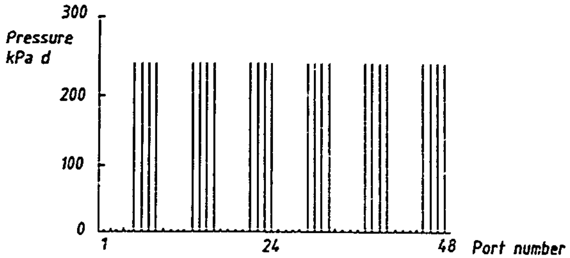


a) Pressure applied to groups of ports, reference to atmosphere

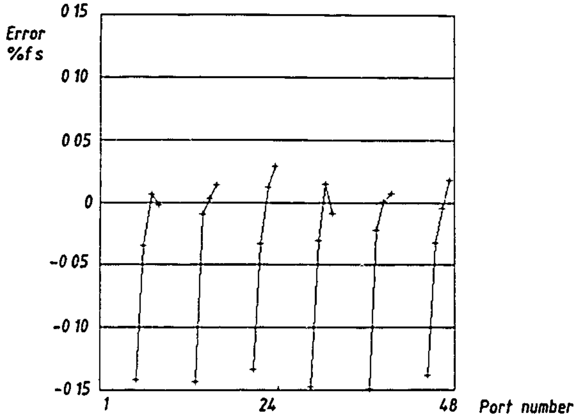


b) Error in response from 24 sensors as a % of full scale (135kPa d)

Fig. 8 ESP scanning head showing carry over



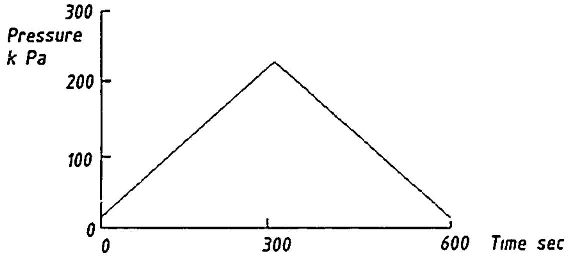
a) Pressure applied to groups of ports, reference to atmosphere



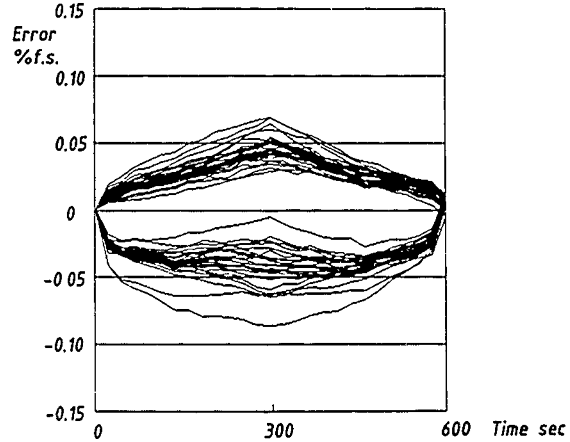
b) Error in response from 24 sensors as a % of full scale (135kPa d)

Fig 9 ESP scanning head showing carry over between ports

Fig 10a&b

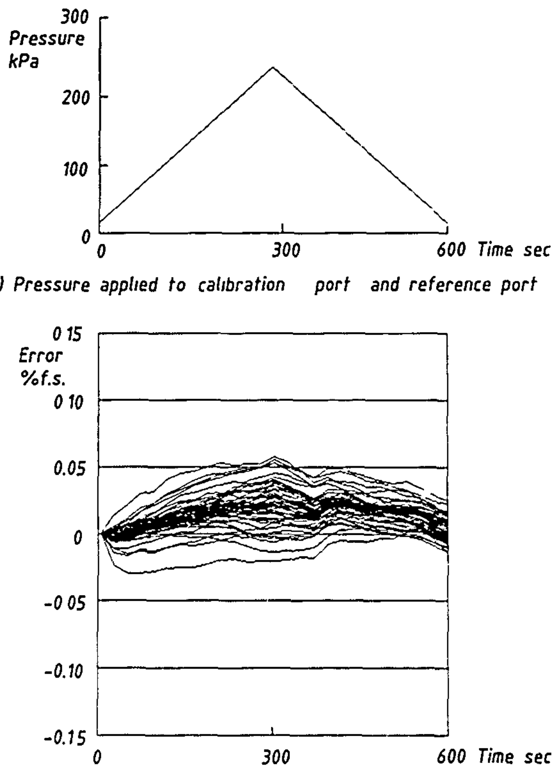


a) Pressure applied to measurement ports and reference port



b) Error in response from 48 sensors as % of full scale (135kPa d)

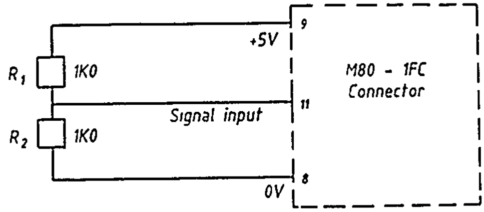
Fig. 10 Common mode response of ESP scanning head with valve in run position



a) Pressure applied to calibration port and reference port

b) Error in response from 48 sensors as % of full scale (135kPa d)

Fig. 11 Common mode response of ESP scanning head with valve in calibrate position



R_1, R_2 50ppm temperature coefficient

Fig 12 Circuit to measure sensor voltage supply rail

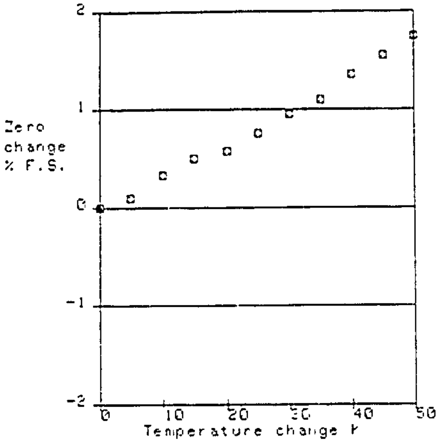


Fig 13 Change in transducer zero output with temperature

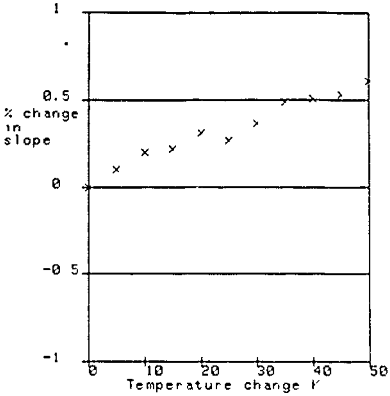


Fig 14 Change in transducer slope with temperature for positive pressures

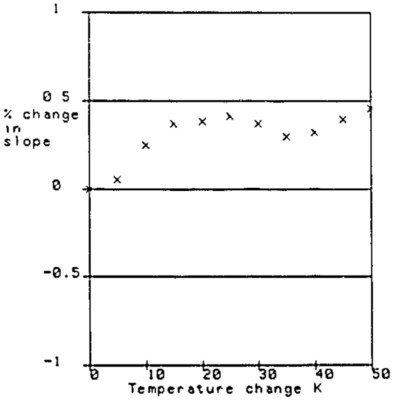


Fig. 15 Change in transducer slope with temperature for negative pressures

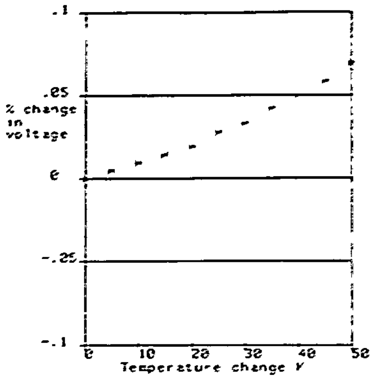


Fig. 16 Change in bridge excitation voltage during temperature experiment

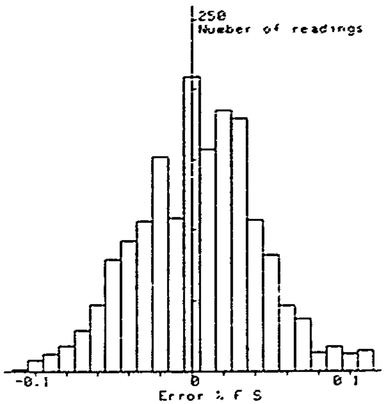


Fig 17 Histogram of error distribution during tunnel calibration

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1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TM Aero 2222	N/A	UNLIMITED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
7672000H	Defence Research Agency, Aerospace Division, Bedford, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title Introduction of electronic pressure scanning at the Royal Aerospace Establishment

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference
Presented at the 37th International Instrumentation Symposium of the Instrument Society of America, San Diego, California, 5-9 May 1991.

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Holmes, J. W.			Oct 1991	27	

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.

15. Distribution statement
(a) Controlled by – DRIC
(b) Special limitations (if any) –
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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Electronic pressure scanning. Wind tunnel instrumentation.

17. Abstract

An electronic pressure scanning system has been installed at the Royal Aerospace Establishment Bedford (UK) and has been used to provide pressure data in wind tunnel tests on aircraft models. This paper contains the results and conclusions from the laboratory experiments that were undertaken to assess the effectiveness of the system in the wind tunnel environment. The paper also contains a summary of the system performance during model tests in the first six months of tunnel running. It is shown that the system offers considerable savings on pressure data gathering times over mechanical pressure switches previously in use. Error analysis of the data from the system has shown that existing high measurement accuracy has been retained. The paper highlights the advantages and disadvantages of using such a system.

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RAE Form A143 (revised October 1980)