<u>*Session 2 - Unsteady Pressure Measurements*</u>

TEMPERATURE ERROR COMPENSATION APPLIED TO PRESSURE MEASUREMENTS TAKEN WITH MINIATURE SEMICONDUCTOR PRESSURE TRANSDUCERS IN A HIGH SPEED RESEARCH COMPRESSOR

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SUMMARY

An easily implemented system has been developed for the compensation of temperature errors for measurements taken using miniature semiconductor pressure transducers. Data have been taken, using this compensation system, from a single-sensor traverse probe in a high speed research compressor. This paper discusses the system and its implementation, and makes comparisons of the transducer measurements with conventional pneumatic data. An automated facility for steady state pressure and temperature calibration of transducers is also described.

1. INTRODUCTION

Propulsion Department of The Royal Aerospace Establishment is engaged in a programme to investigate unsteady viscous flows within high-speed axial compressors and fans. Aerodynamic traverse probes containing miniature high-frequency response pressure transducers are used for this study, as are transducers mounted in compressor blades and in removable casing modules. Unfortunately the strain gauge elements, that sense pressure transducer diaphragm deflection, are prone to changes in resistance with temperature because of their high thermal coefficient of resistance. Consequently, the transducer pressure sensitivity and null pressure reading (or zero-offset) change with temperature (see Fig 1)*. Hence significant pressure measurement errors arise if the sensitivity and zero-offset, used to convert the transducer output voltage to pressure, are not those associated with the temperature being experienced by the transducer diaphragm while taking the measurement (see Fig 2)*. This characteristic has traditionally limited employment of such transducers within high-speed compressors where large span-wise, stage-wise and throttle-setting related temperature variations are found. However, while the temperature sensitivity of these transducers is a drawback their use is attractive because of their ability to record the fluctuating pressure field. This is not only of fundamental interest because of the information provided on the unsteady nature of the flow itself, but it also provides the means with which to determine accurately time-averaged pressure levels from the digitised transducer output. This is difficult to accomplish using conventional pneumatic pressure measurements because of system averaging errors, especially when measuring the highly pulsatile pressure field near high-speed compressor rotors.

This paper discusses an easily implemented system to provide active transducer temperature error compensation which enables transducers to be used as absolute pressure sensors. Implementation of the system is discussed and compensated

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* The measurements in Figs 1 and 2 relate to a Kulite type XCQ-062-5OA transducer coupled to the manufacturers passive resistance network. The transducer temperature sensitivity is within manufacturers specification.

time-averaged total pressure measurements taken in a high-speed research compressor are presented. An automated transducer calibration facility is also described.

2. TEMPERATURE ERROR COMPENSATION SYSTEM

At RAE Welsh and Pyne (1980) showed that if a transducer is excited with a regulated constant voltage, changes in strain gauge bridge resistance induce a change in current drawn by the bridge which can in turn be sensed as a change in voltage across a stable (ie < 5 ppm/°C) 'sense' resistor placed in series with the transducer polarising voltage. While this approach (or variations on it) has been utilized in a number of systems already employed in unsteady aerodynamics research (eg Cook (1989), Welsh and Pyne (1980)) these systems have tended to be expensive as well as complicated and time consuming to set up. Further, with both of these systems, once each hardware channel has been set up it becomes dedicated to one particular transducer. Hence a prototype system (Fig 3) was produced at RAE which coupled commercially available signal conditioning amplifiers (Endevco model 4423) to a 'sense' resistance monitoring module. The aim was to produce a relatively inexpensive, easily implemented compensation system that can be integrated into existing digital data acquisition systems. Further, it was seen as attractive that several transducers could be used in conjunction with the same hardware channel (although not at the same time).

Setting-up of the system requires the transducer to be immersed in a chamber where both pressure and temperature can be varied. Hence, the transducer can be calibrated and its pressure sensitivity and zero-offset determined from the transducer output (V_O) for a range of constant temperatures. Similarly the 'sense' voltage (V_S), which is largely independent of pressure, is recorded. Subsequently, the variations of V_O and V_S are coded into a data processing program. Hence, during compressor measurements, V_S is used to determine the transducer diaphragm temperature which in turn is used to derive the associated pressure sensitivity and zero-offset in order to convert V_O to the correct absolute pressure level. Note that while V_O is a measure of the fluctuating pressure sensed by the transducer over a wide bandwidth, V_S is a measure of the steady-state temperature of the diaphragm only, due to the high thermal inertia of the strain-gauge bridge network.

3. TRANSDUCER CALIBRATION DRIFT

The success of the compensation method relies upon the transducer performance not changing significantly with time and hence being described accurately by the variation of V_O and V_S coded into the data processing software. However, measurements taken at RAE have recorded 'calibration drift' of up to 1% of transducer full scale deflection over several weeks for some transducers. Zero-offset and sensitivity drift for a typical Kulite type XCQ-062-50A transducer are shown in Fig 4. While not all transducers have exhibited such significant drift all of the transducers tested to date have been prone to drift to some extent, although the reasons for different drift performance have yet to be identified. From Fig 4 it is evident that transducer measurements taken between the initial calibration and that on day 4 would be subject to less calibration drift uncertainty than those taken between calibrations on day 4 and day 72. However, the compressor test measurements, described later, were taken on various days between day 4 and day 72 and it was not until after completion of the test series that the extent of the drift was fully appreciated. Hence, although drift was quantified over the test series, the measurements would have benefited from more frequent calibrations. The lesson from this experience is that where possible, transducers should be calibrated on several occasions prior to a test series. This may allow selection of transducers with the most favourable characteristics and would determine the frequency with which the selected transducers need to be re-calibrated during the test series in order to attain acceptable levels of absolute pressure measurement uncertainty.

4. AUTOMATIC TRANSDUCER CALIBRATION FACILITY

It is evident that implementation of the compensation system requires repeated careful calibration of the transducers. As this must be done at a range of temperatures, and may involve many transducers in a large test programme, it can become burdensome. Hence an important part of the instrumentation system development at RAE was to provide an automated transducer calibration facility. This is shown schematically in Fig 5 and illustrated in Fig 6. Central to the system is a 30 cm diameter autoclave of 10 litre internal volume into which the transducers are placed. A large chamber volume was seen as necessary so that transducers mounted in compressor and fan blades, as well as in removable casing modules, can be calibrated. Also, several aerodynamic traverse probes can be calibrated simultaneously.

The autoclave is surrounded by a heating element capable of raising the chamber temperature to 573K while an internal stirring fan ensures uniform temperature. The chamber is rated to withstand pressures from near-vacuum to 688 kPa. Pressure is controlled to within 0.14 kPa of set level by a Druck DPI500 pressure controller, while absolute pressure level is measured (to an accuracy of ±0.02% of reading) using the combination of a digital barometer and a pressure gauge. Temperature is controlled by a programmable digital controller and is measured by several platinum resistance thermometers mounted within the autoclave. The calibration sequence is supervised by a micro-computer which interfaces with the temperature controller and the digital barometer. In addition, the system controls external and internal cooling coils via an analogue output channel. The system also logs the test transducer outputs. Presently 32 analogue input channels are available, however this can readily be extended to 256. For the purpose of setting-up transducer compensation a typical calibration consists of an 11-step pressure cycle (ie datum pressure to full scale deflection to datum pressure) at 7 different temperatures. This is normally accomplished within 18 hours.

5. COMPRESSOR MEASUREMENTS

This section presents compensated time-averaged absolute total pressure measurements taken behind the first three rotors of the C147 high-speed five-stage research compressor. This compressor has been described briefly by Cherrett & Bryce (1988) and referred to by Calvert et al (1989). The measurements were taken using three traverse probes containing single Kulite type XCQ-062 (344 kPa absolute) pressure transducers mounted 1.65 mm below a pneumatic Pitot tube as shown in in Fig 7. Two of the transducers employed a 0.07 mm thick coating of Silastomer rubber to protect the pressure sensing diaphragm, while the third utilized a perforated (Kulite type B) screen for protection. The relative size of the probes to the rotor rows traversed is shown in Fig 8. The transducer signals were recorded by a data acquisition system which has been described by Cherrett & Bryce (1988). The time-averaged pressure levels were determined from phase-locked average measurements which were processed from data taken over 128 consecutive rotor revolutions. The data were sampled at 1 MHz which is approximately 100-times the blade passing frequencies encountered in the compressor. Measurements were taken while the compressor was operating at three points on the 95% speed characteristic. The operating points, defined as near choked flow, peak efficiency, and near surge, are shown in Fig 9. Fig 10 shows the time-averaged total pressure profiles derived from the unsteady transducer measurements taken at the three operating points behind the first, second and third stage rotors. Uncertainty in the data, due to calibration drift equates to ±2.7%, ±0.8% and ±1.1% of reading for the first, second and third rotor measurements respectively.

Fig 11 compares the transducer measurements with the adjacent Pitot pressures taken at the same time. The first rotor measurements, which were taken at peak efficiency operation, agreed to within 2-3%, as do the second rotor measurements. Adjacent Pitot measurements were not taken at peak efficiency operation for the third rotor hence near surge measurements are shown in Fig 11. This comparison also shows that the pneumatic and transducer results agree very well. While such agreement is encouraging it should be noted that the pneumatic results may be prone to pneumatic system averaging errors. In practice, these are difficult to predict with confidence, although the pneumatic system frequency response characteristics were predicted using the methods described by Hougen et al (1963). For the configuration used, a 15 m tube of 1.57 mm internal diameter, a natural resonant frequency of 30 Hz and a damping ratio of approximately 3.0 was predicted. Clearly, in future work, where transducer drift related uncertainty is reduced to suitable levels it would be interesting to attempt a more rigorous analysis of pneumatic system accuracy in parallel.

At this point it is pertinent to note the importance of measuring transducer diaphragm temperature each time a pressure measurement is taken. Fig 12 shows two pressure profiles measured behind the third rotor of C147 at peak efficiency operation. Profile X has been derived with the compensation system taking account of spanwise temperature variations and their effect on diaphragm temperature. Profile Y was derived by suppressing the compensation system such that a uniform spanwise temperature, equal to that measured at mid-span, was assumed. Clearly without active temperature compensation, based on actual diaphragm temperature variations, the pressure profile cannot be defined accurately. In this case, the two profiles disagree by up to 1.6% if increases of temperature toward the endwalls are not taken into account.

6. TOTAL TEMPERATURE MEASUREMENTS

The primary aim of the compensation system is to correct for transducer thermal errors utilising a measurement of transducer diaphragm temperature. However, it is attractive to correct this measurement for convective heat transfer effects and hence obtain a measure of flow total temperature. To this end, the recovery factor of the 'B-screen' transducer was measured in an open jet wind tunnel. These results are shown in Fig 13 where it can be seen that diaphragm recovery factor is Mach number dependent. This is a disadvantage if flow Mach number is not known accurately. Since spanwise static pressure measurements were not taken behind the rotors in C147 it was not possible to define spanwise Mach number distributions. Hence a first order estimate of Mach number was made assuming uniform casing wall static pressures at rotor exit. Measurements taken behind the first rotor in C147 and converted in this manner are shown in Fig 14 where they are compared with Kiel-type thermocouple sensors mounted on the first stator leading edge. Quantitative agreement between these measurements is not very good, with approximately 4K difference at mid-span at each compressor operating point. This can be partially explained by the Mach number approximations used as well as by deficiencies in the absolute accuracy of the recovery factor calibration. More work is required if full advantage is to be taken of this attractive consequence of utilizing the pressure transducer compensation system.

7. CONCLUSIONS

1 A reliable and easily implemented approach to correcting semi-conductor transducer temperature errors has been applied successfully. Comparison between transducer time-averaged pressure measurements and pneumatic pressure measurements shows agreement within 2-3%.

2 An automated transducer calibration facility has been commissioned which is capable of calibrating transducers at temperatures between ambient and 573K and for pressures ranging between near-vacuum and 688 kPa. The pressure chamber is capable of accepting large instrumented structures of up to 30 cm diameter and 20 cm high.

3 Transducer calibration parameters have been observed to vary with time. The implication of this behaviour for the experimental aerodynamicist is that prior to embarking upon a test series transducers should be calibrated several times over a period of time comparable with the test programme in order to ascertain the magnitude of drift. This may allow selection of transducers of more favourable performance and will define the frequency with which it will be necessary to re-calibrate the transducers during the test series in order to maintain desired pressure measurement uncertainty levels.

4 Utilisation of the temperature compensation system offers the capability to measure flow temperature using transducer diaphragm temperature measurements. Preliminary work to determine transducer diaphragm recovery factors suggests that they are Mach number dependent. More work is required if advantage is to be taken of this approach.

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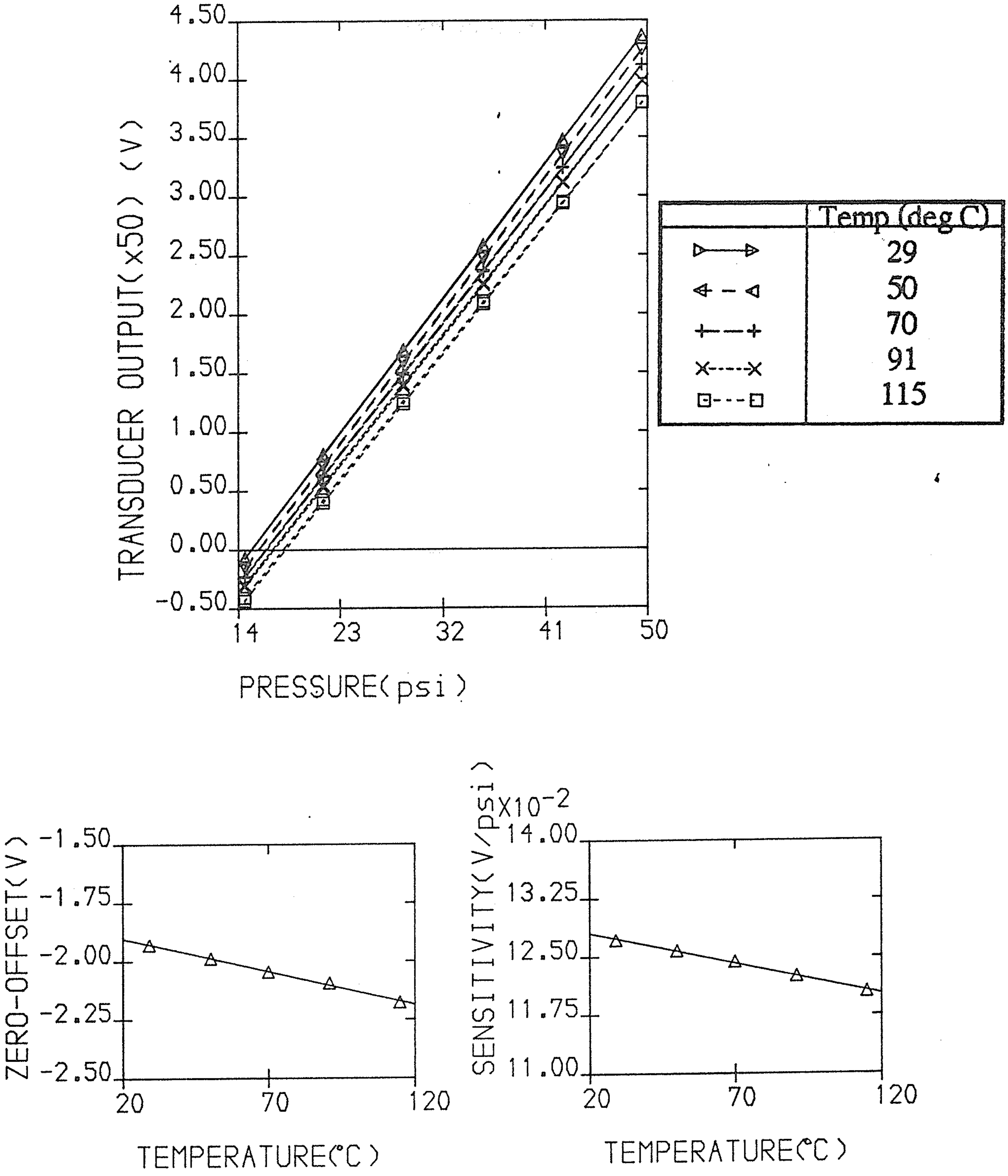

Fig. 1 The effect of temperature on transducer zero-offset & sensitivity.

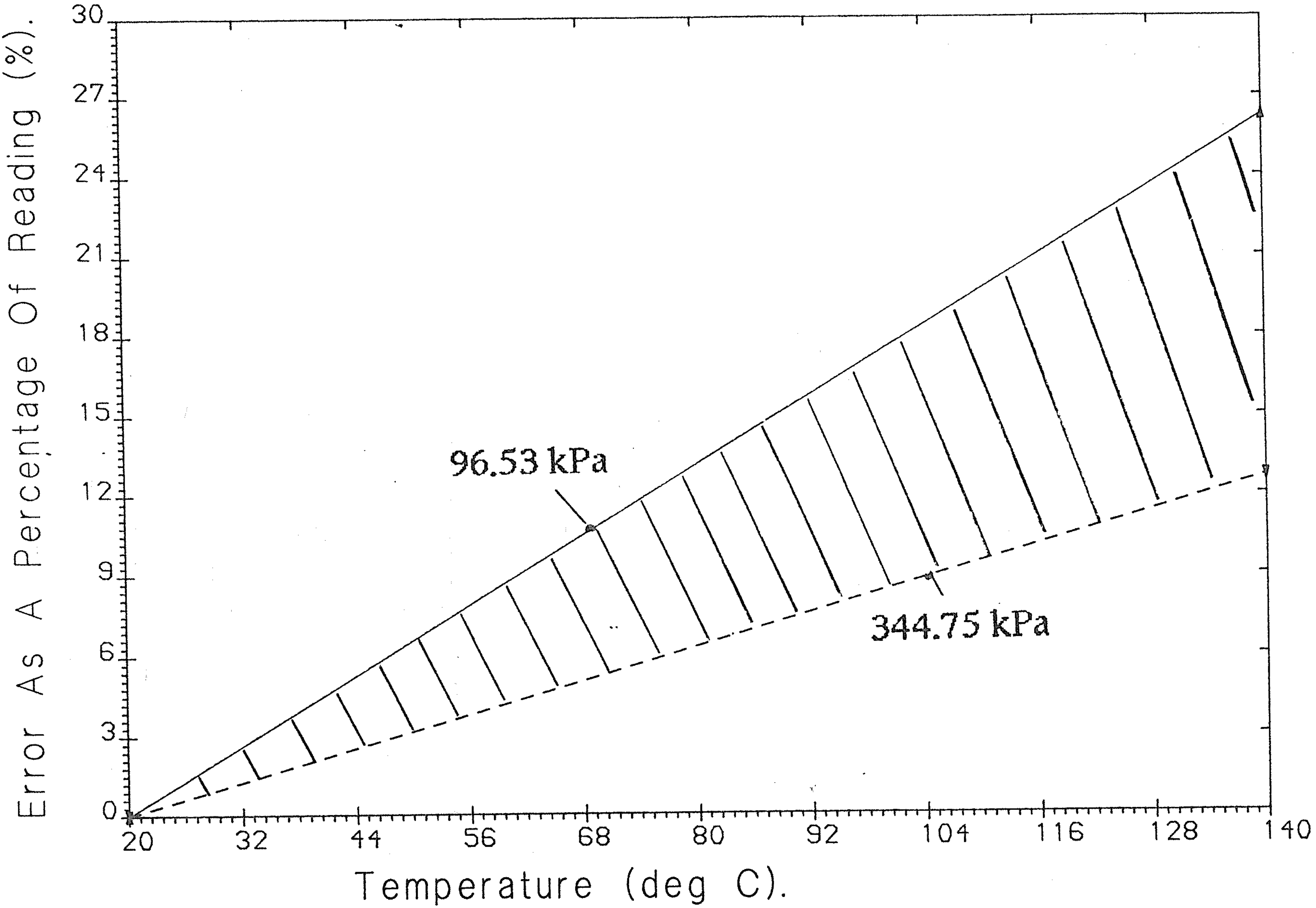

Fig. 2 Typical transducer pressure measurement error (Kulite xcq-062-50psia with passive compensation network).

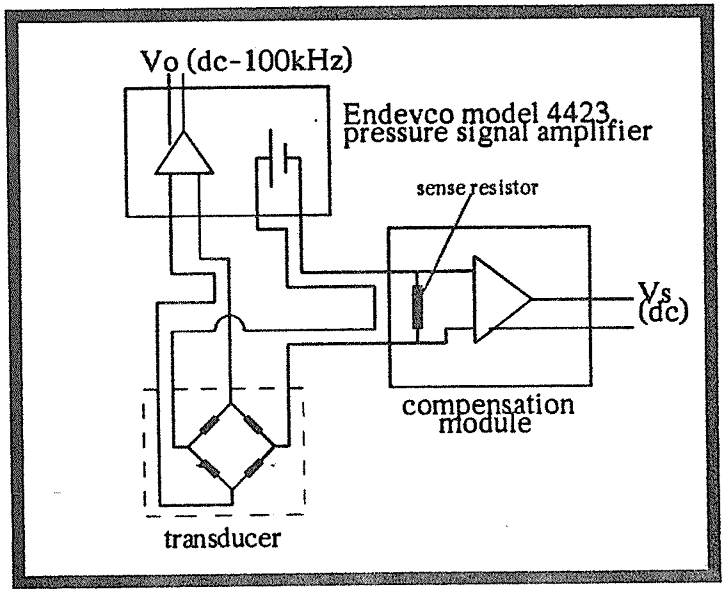

Fig. 3 Schematic of the prototype compensation system.

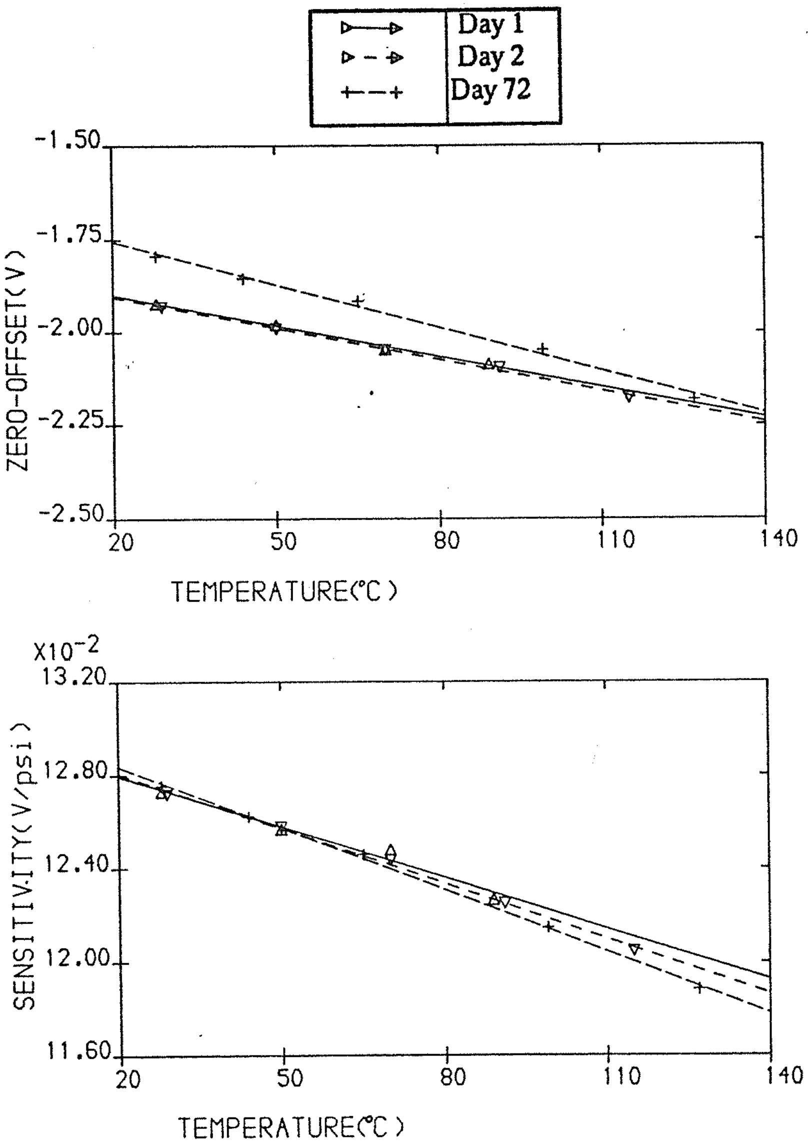

Fig. 4 Transducer calibration drift manifest in transducer zero-offset & sensitivity.

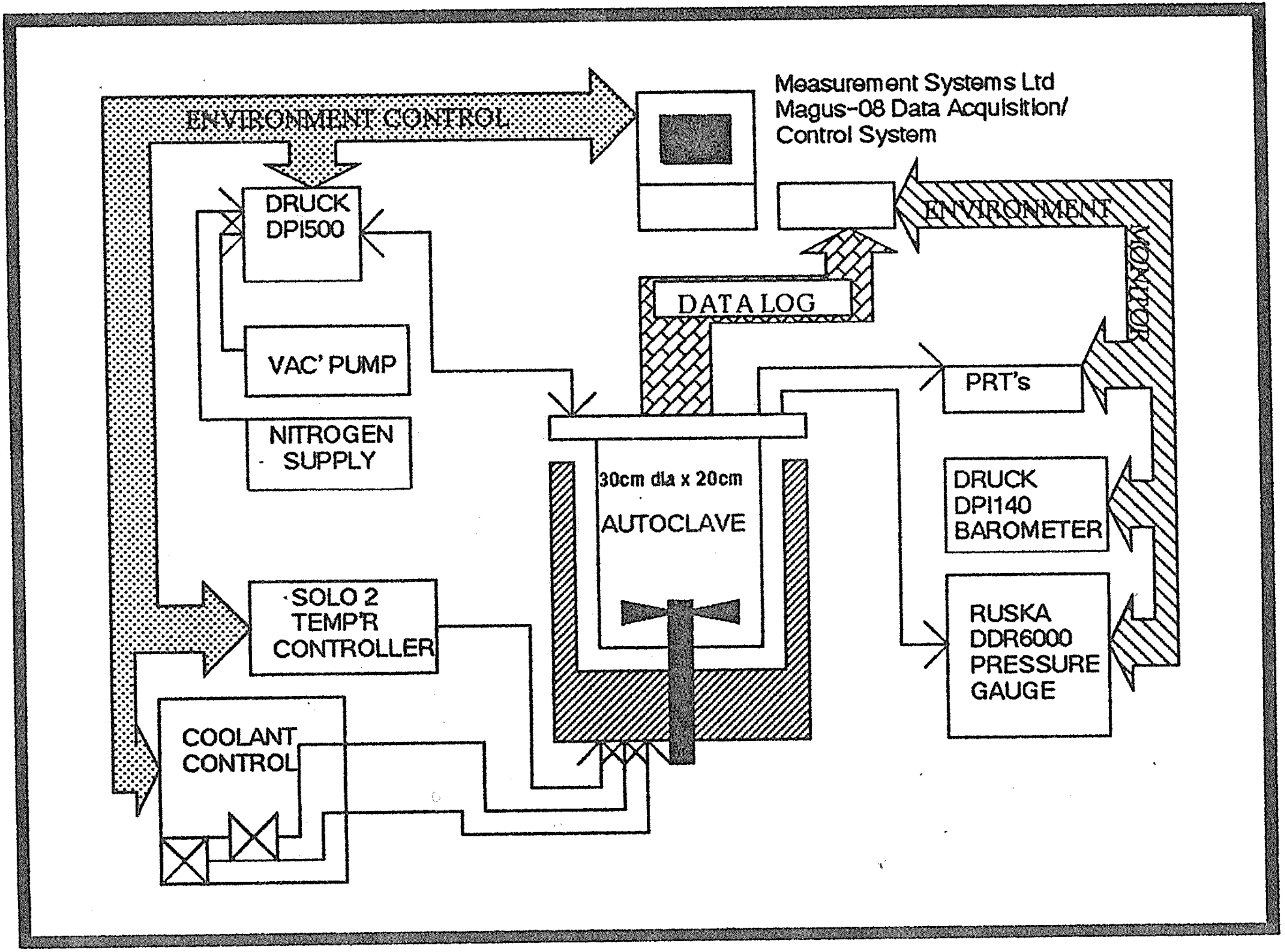

Fig. 5 The automatic calibration facility.

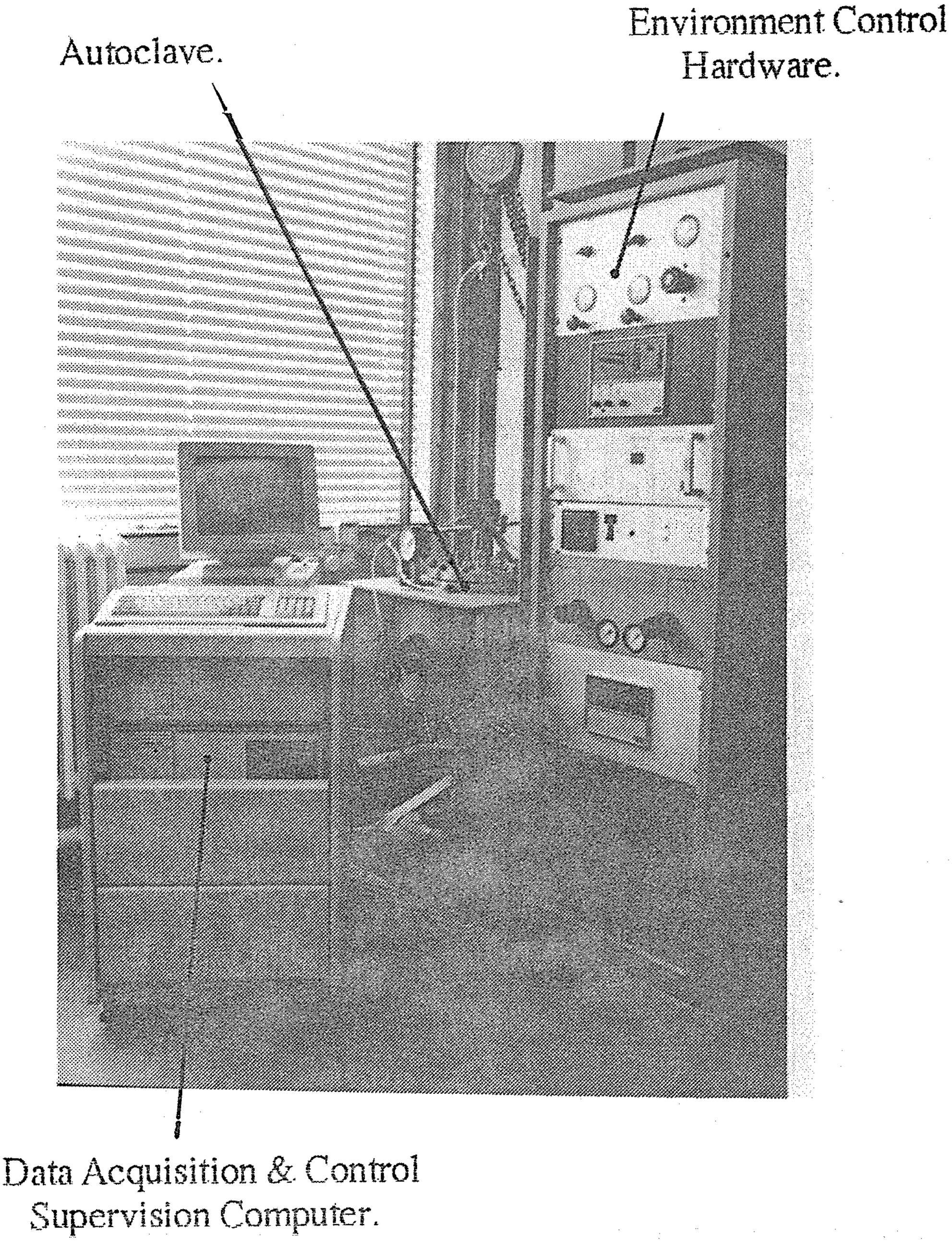

Fig. 6 The automatic calibration facility.

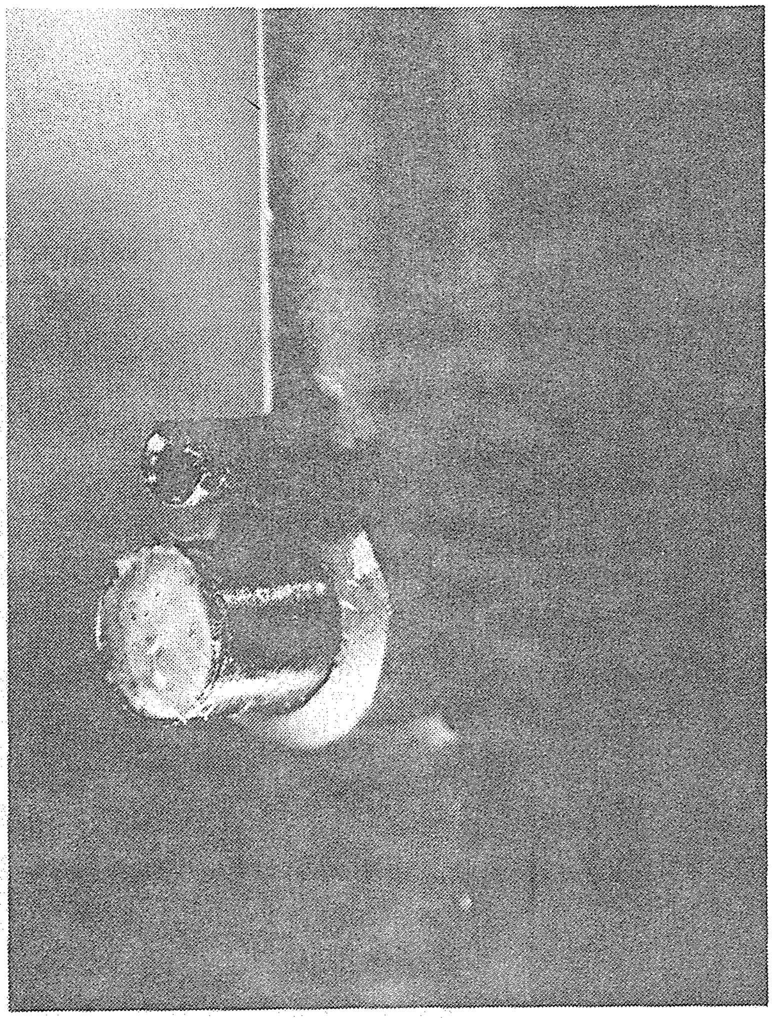

Fig. 7 High-response traverse probe.

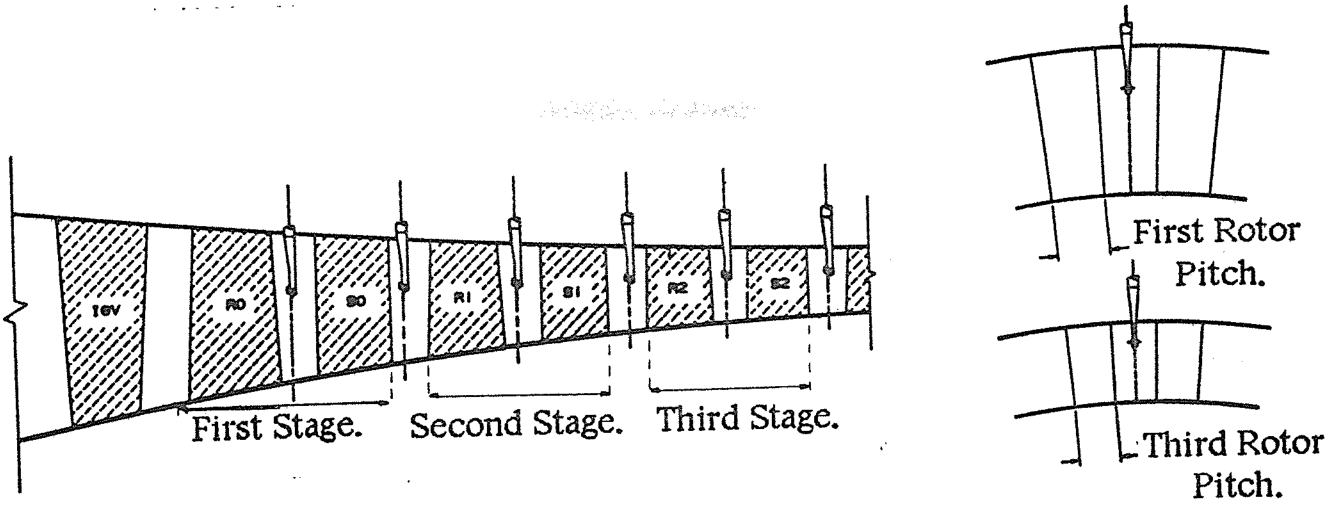

Fig. 8 The size of the traverse probe relative to the blade rows traversed.

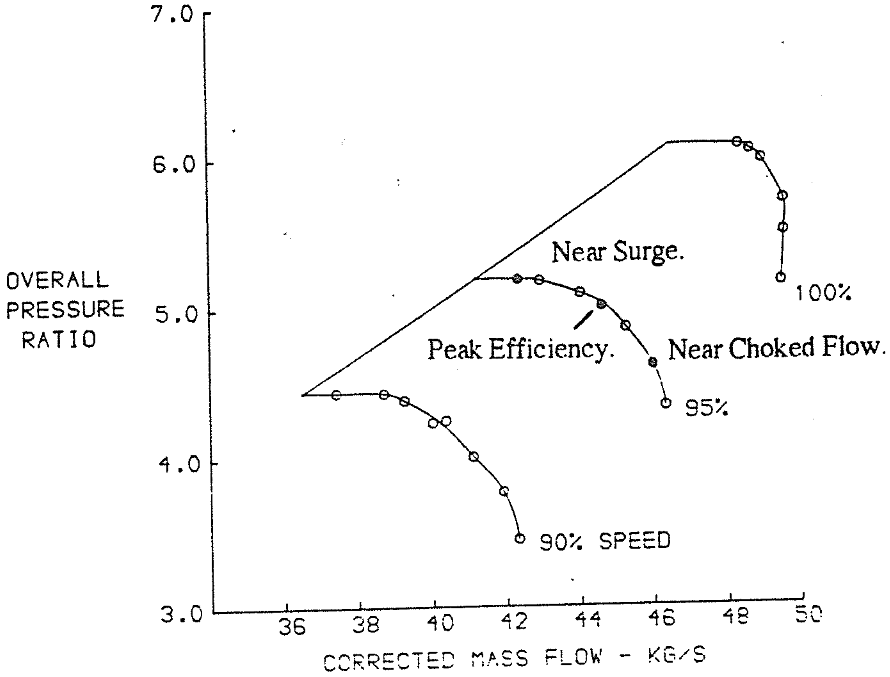

Fig. 9 C147 build 2 performance map.

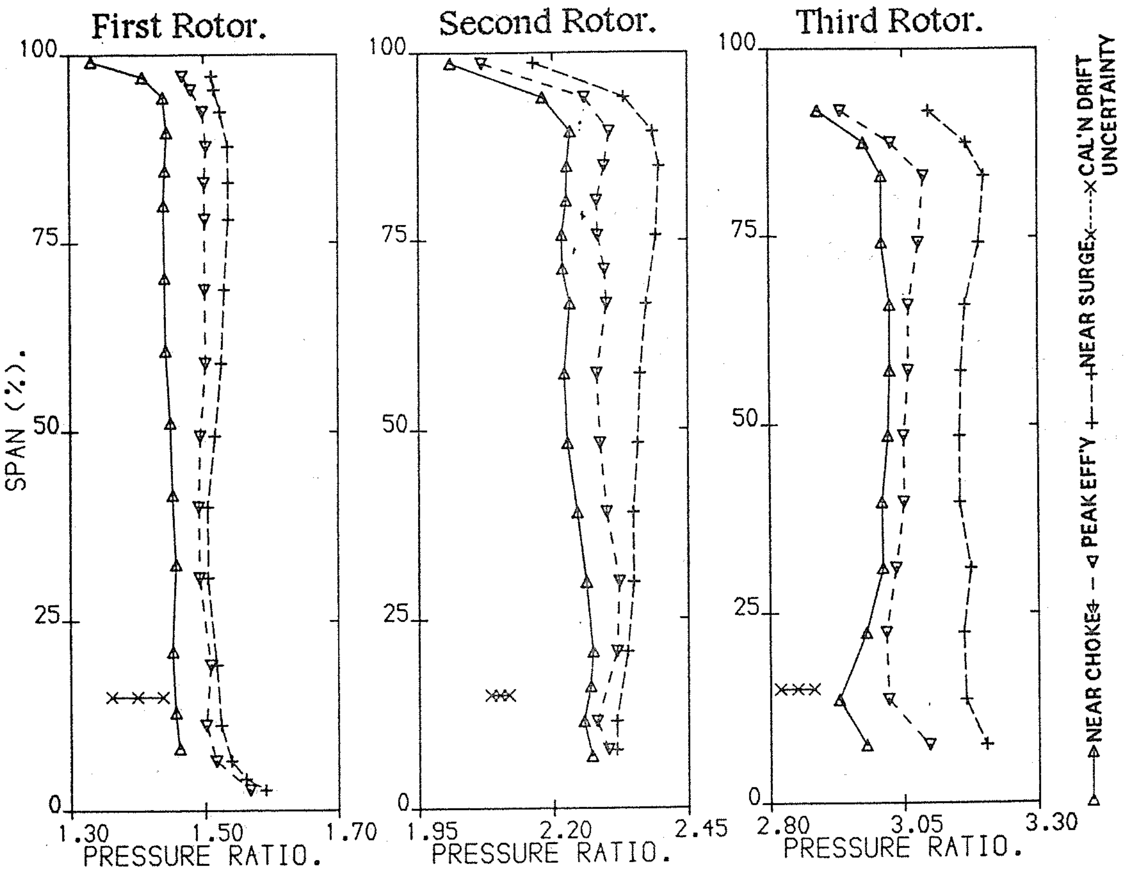

Fig. 10 Time-averaged rotor exit total pressure measurements derived from the transducer measurements.

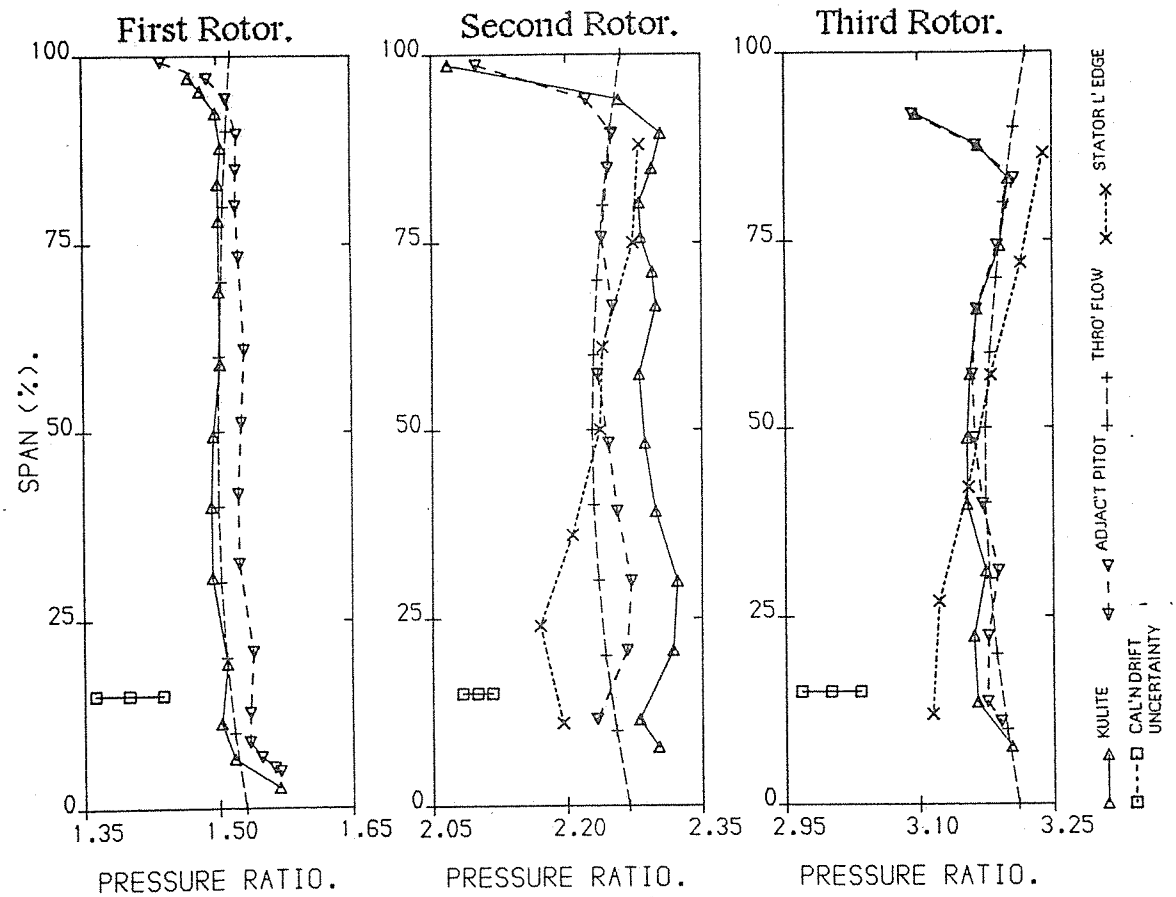

Fig. 11 Comparison of the transducer measurements with alternative data.

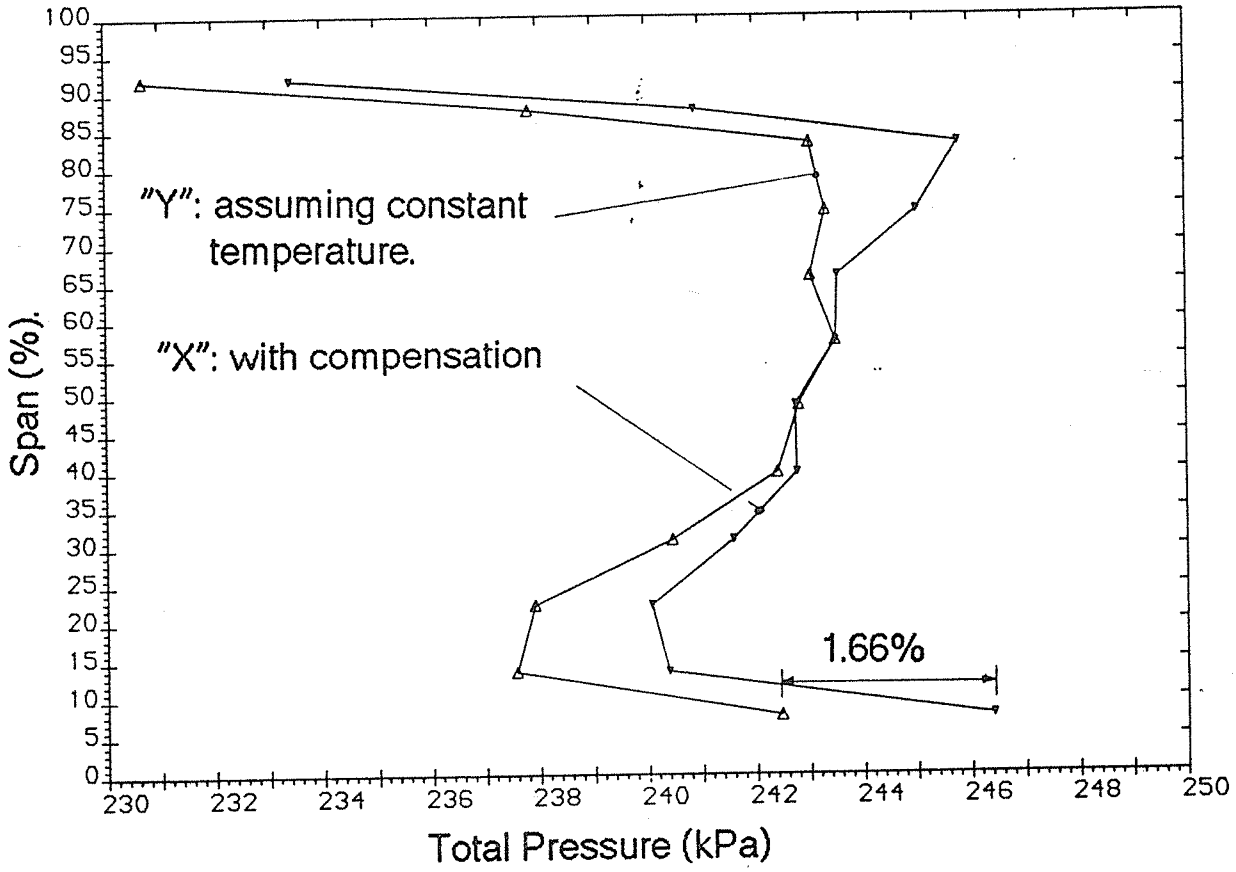

Fig. 12 The effect of compensation on spanwise pressure profile definition.

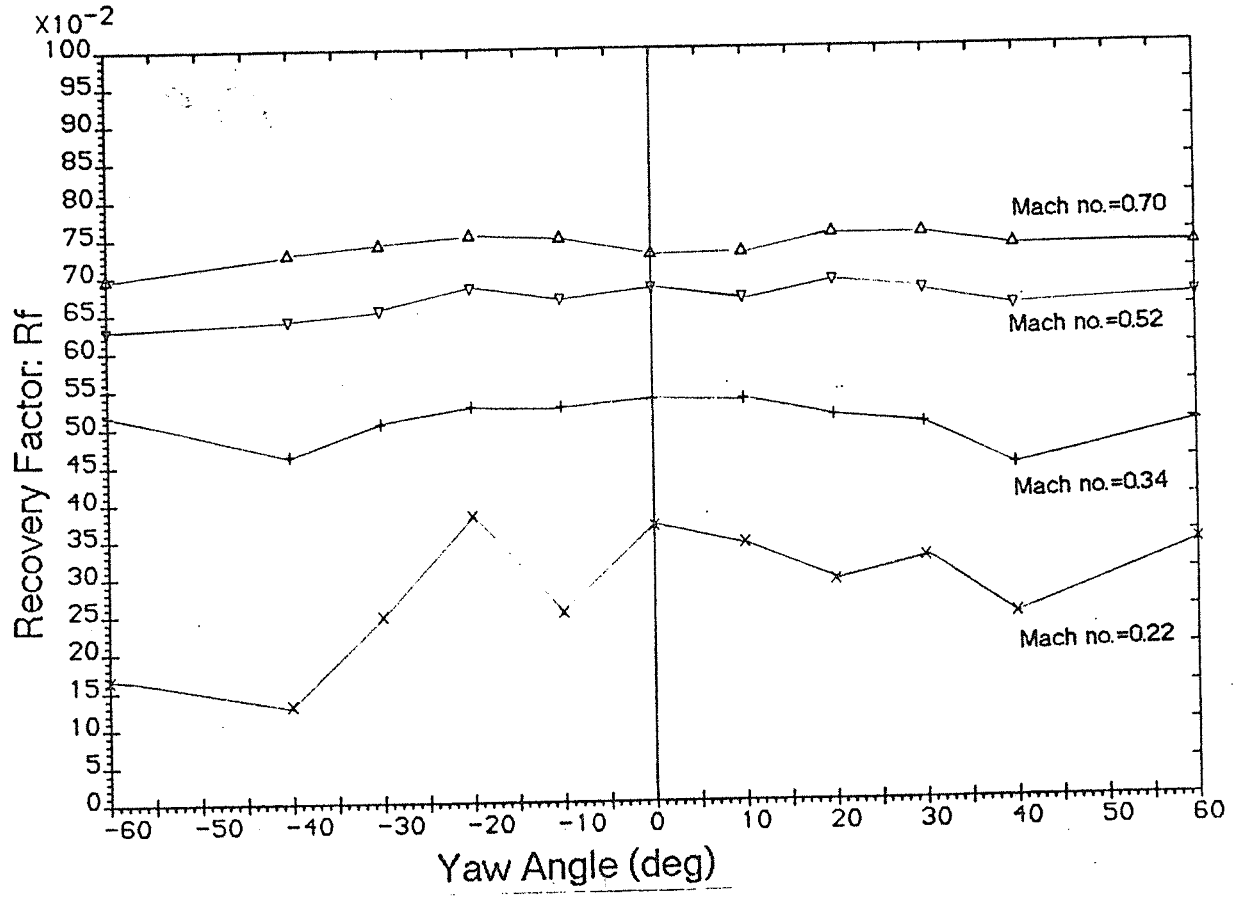

Fig. 13 Recovery factor measured using a 'B screen' transducer.

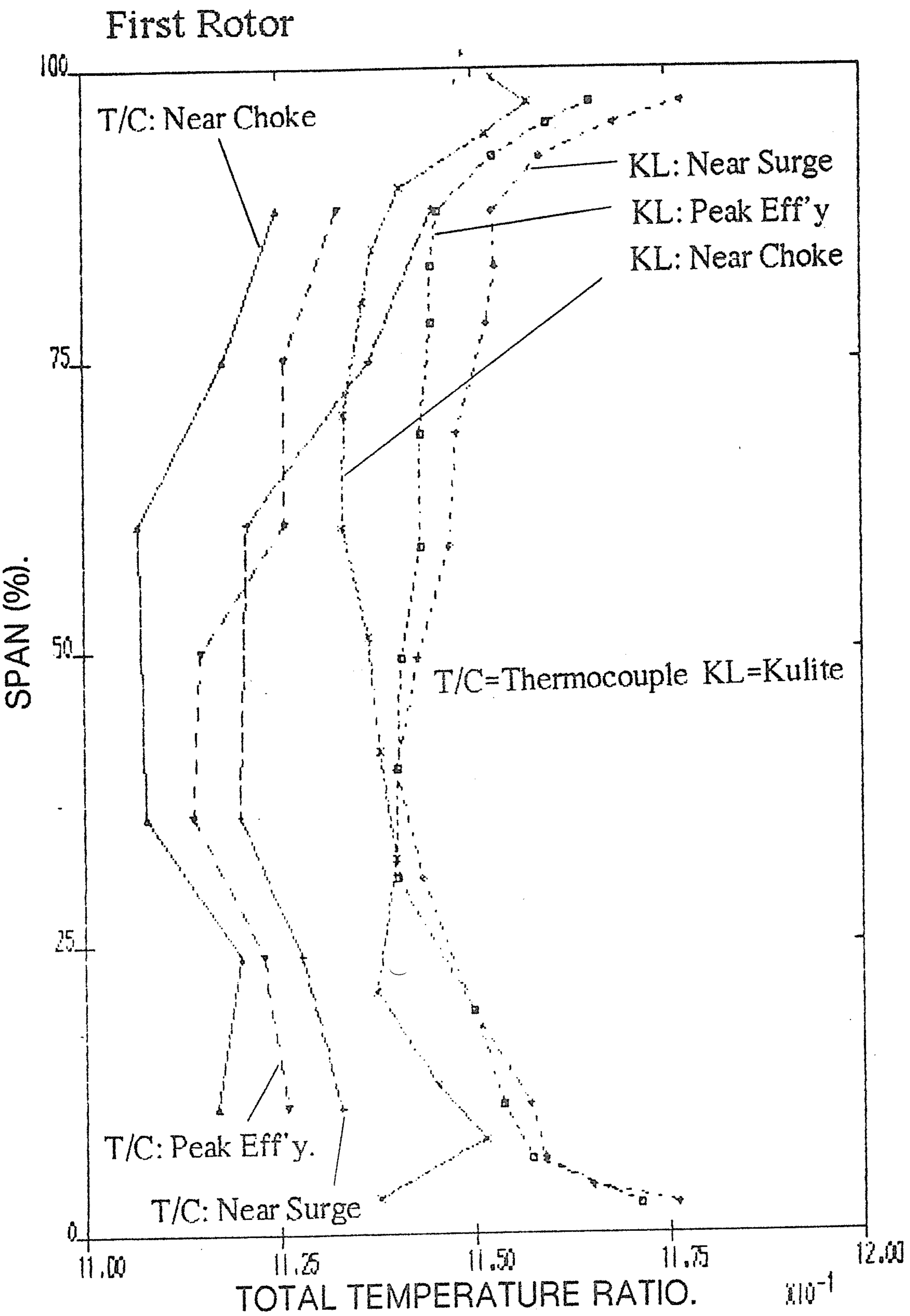

Fig. 14 Comparison of transducer diaphragm derived temperatures with those measured using shielded thermocouples.