Presented at “XVth biennial Symposium on Measurement Techniques in
Transonic and Supersonic Flows in Cascades and Turbomachines”, Florence 2000

Acceleration Insensitive Semiconductor Pressure Sensors For High Bandwidth Measurements On Rotating Turbine Blades

A.D. Kurtz [1], R. W. Ainsworth [2], S.J. Thorpe [2], and A. Ned [1]

1
Kulite Semiconductor Inc.
1 Willow Tree Road,
Leonia,
New Jersey,
U.S.A.

2
Department of Engineering Science,
Oxford University,
Parks Road,
Oxford.
U.K.

Abstract

The turbine environment is a harsh one in which to attempt fast response measurements of static pressure on a rotating component, even for model turbines operating at ambient temperatures. Because of the high rotational speed of most turbines, pressure sensors can be exposed to high levels of centrifugal and vibrational acceleration. Indeed, some recent experiments have been designed with high vibrational levels of acceleration deliberately introduced to permit the study of aeroelastic behaviour – the coupling of structural response with aerodynamic excitation.

Semiconductor pressure sensors function by determining the deflection of a small silicon diaphragm under exposure to a normal stress (pressure), using a Wheatstone bridge network of strain gauges to measure this movement. However, the diaphragm will also deflect under the influence of centrifugal and vibrational accelerations, and the experimenter must be aware of these effects, and try to take them into account.

In this paper, the design of a new semiconductor sensor is presented which compensates for these deleterious effects. The construction of the device is described, and preliminary calibration performance discussed. Finally, results from tests to exposure to high levels of centrifugal acceleration are presented, demonstrating the operation of the device in a manner that was intended when it was designed. Potential applications in the turbomachinery area are also outlined.

1. Introduction

The measurement of pressures in the context of turbomachinery operation has been an important means of investigating the operation of gas turbines since their invention. The drive in recent times has been the accurate measurement of ‘unsteady pressure’, so that time-varying phenomena can be assessed and taken into account in the design process. In terms of blade aerodynamic profile design, the desire is to measure both total and static quantities on stationary and rotating components to bandwidths of order 100 kHz. Pressures are required to calculate gas loading on other parts, such as rotor discs, labyrinth seals, de-swirl vanes and the like. In addition to pressures on components, the efficiency of an engine is highly dependent on the orderliness of the air-flow through the machine, and to this end the engineer would like to assess the time-resolved three-dimensional gas flows (yaw and pitch angle, Mach number, total pressure) in all stages of the compression and expansion processes.

Much progress has been made in achieving some of these goals with the semiconductor-based piezoresistive silicon pressure diaphragm. Equally there is continuing interest in improving the applicability of these devices to more challenging measurement applications. The silicon sensor, in addition to being sensitive to pressure, is also sensitive to temperature, base strain and inertial stresses in the diaphragm material when subjected to accelerations, whether caused by rotation or vibration. Of these, it is the sensitivity to acceleration which generally has the largest effect. This can be accounted for by way of calibration - the size of a correction can be related to the known acceleration vector. There may however be some applications (for instance in aeroelastic work where blades are vibrating in an unquantifiable manner) when it is more desirable to have a sensor which is insensitive to acceleration fields. The purpose of the present work is to investigate the feasibility of such a device. First it will be necessary to understand the operation of a conventional piezo-resistive sensor.

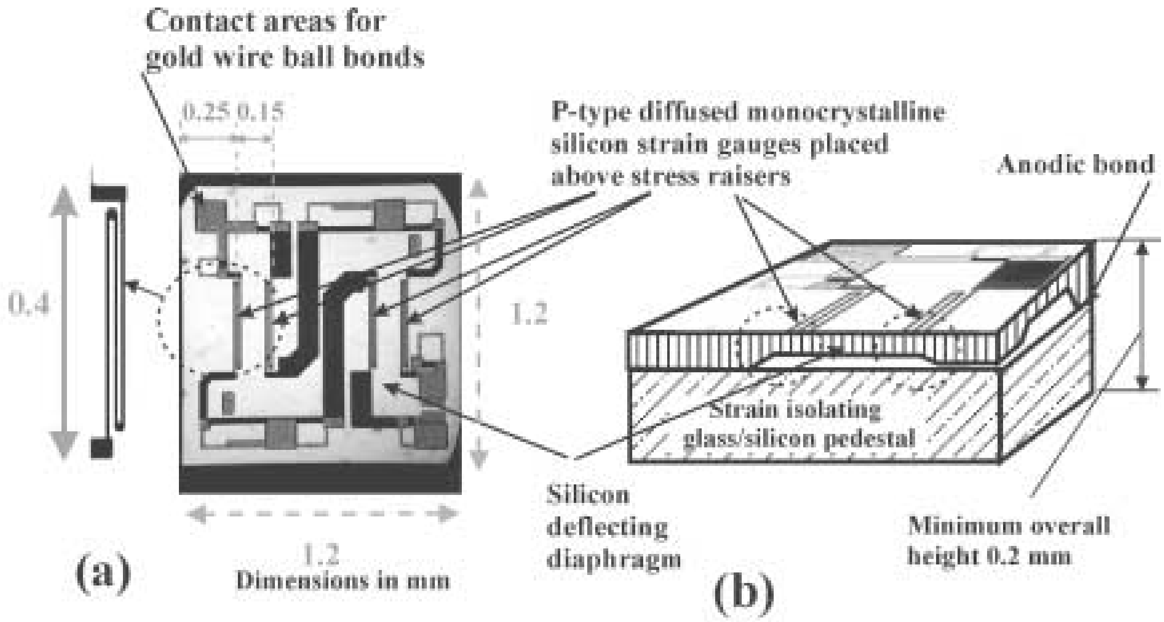

Figure 1: (a) Photograph of silicon die, showing piezo-resistive strain gauge elements (b) One quarter section of silicon die plus strain isolating pedestal

2.Piezo-resistive pressure sensors

There are two core elements of the current generation of devices which will be considered in turn: the production of a suitable deflecting diaphragm to turn applied stress into displacement, and the addition of piezoresistive strain gauge elements to the diaphragm to record the displacement.

Referring to figure 1a and 1b, the silicon wafer itself is micro-machined on its rear surface, using photolithographic techniques in conjunction with a phosphoric acid etch along preferred crystallographic planes. The purpose of this machining is to turn it into a suitable deflecting diaphragm when subjected to a normal stress (pressure) on the front face. The micro-machining of a non-uniform section enables varying values of surface strain to be achieved in the front face under deflecting conditions, and the sensor designer, using modern three-dimensional finite element techniques, will decide where to place the semiconductor strain gauges. A sensor with a plan section of 1.2 mm by 1.2 mm is shown in figure 1a, where four individual strain sensors may be observed (one is highlighted with a dotted circle). Individually, these typically comprise three passes 0.4mm long 0.01 mm wide, connected in serpentine configuration, their construction being described below. The thickness of the silicon die at its minimum section is the parameter which determines the nominal pressure range of the device, all other features remaining invariant. A diaphragm thickness of 12.5 m at the thinnest section indicated would be required for a full-scale pressure rating of 0.3 bar pressure difference across the diaphragm, rising to 50 m for a 1.5 bar differential. A non-uniform thickness is used to promote stress raising features, which in turn yield higher surface strain in the front face of the die. The piezoresistive strain elements are placed close to these, as indicated by the one quarter section view in figure 1b. In terms of diaphragm shape, rectangular diaphragm designs have largely replaced the earlier circular versions, the precise placement of linear gauge elements at stress concentration features being easier in the case of the former, orthogonal diamond cuts may then be used to divide up the silicon wafer in order to produce the individual die.

In the example illustrated in figure 1a, four p-type semiconductor piezoresistive strain gauges were formed by diffusion of an impurity through a photolithographic mask. The silicon wafer was placed in a furnace for 30 minutes at a temperature of 1150 ^{0}C and exposed to boron gas to form a p-type piezoresistor. The mask itself requires careful alignment with the stress raising features on the rear, such that two resistive elements will be positioned to experience compressive strain and two tensile. The piezoresistive elements are connected together electrically into a Wheatstone bridge network. Typically, the bridge has an input and output impedance of order 1 K , though values in the range 400 to 2 K are not unusual. A network of conducting pathways produced by the sputtering of (for example) a platinum/titanium alloy provide the electrical conduction paths between the elements. The completed silicon die is anodically bonded to a (strain isolating) pedestal. This is usually constructed from either pyrex glass or silicon. If silicon is used, because of its superior Young Modulus, the height of the whole assembly may be reduced to as little as 0.2 mm, although a figure of 0.38 mm is more typical. As the diaphragm deflects under pressure the resistances of the piezoresistive elements change in value causing the Wheatstone bridge network to move out-of-balance. The application of electrical excitation to this bridge (usually 5 V) produces a bridge output voltage proportional to the applied pressure (typically 100mV for maximum operating deflection). Careful diaphragm design will ensure that this relationship is keep close to a linear one. The sensitivity (units V/Pa) is termed the sensor span. Naturally, if the elements are of equal resistance, there will be a zero output voltage with no pressure differential across the diaphragm, although more usually there is some small voltage, termed the offset voltage. Both of these characteristics are determined by calibration.

In addition to the basic pressure sensitivity of the silicon sensing device, three other sensitivities have been mentioned. The first of these, temperature sensitivity, is easily dealt with using temperature compensation schemes (Epstein, 1985; Ainsworth et al 1991; Ainsworth et al, 2000) of which there are a great plethora. This arises as follows: the resistive impedance value of the piezoresistive elements depends not only on the strain they experience but also their temperature for two reasons: the strain gauge factor (change in resistance per unit of strain) of each element depends on the electrical properties of the p-type semiconductor created; and the element resistance itself (even in the absence of strain) is also a function of temperature. Given that the output of the sensor is linear with applied pressure, these two effects change the values of sensor span and offset, and the variation with temperature of these values is termed span and offset sensitivity.

The second sensitivity, termed base strain sensitivity, is caused by strain transmitted into the sensor diaphragm from the underlying parent material on which the sensor is mounted. For instance, in the case of a turbine blade, a strain field will be set up in the surface of the blade due to rotation. It is the function of the strain isolating pedestal in figure 1b to reduce the value of the strain induced in the diaphragm by this mechanism. In any case, this effect can be calibrated, and is usually small enough to be neglected. Being more specific (Ainsworth el al, 2000), typical results for this kind of calibration gave a base strain sensitivity of -0.00164 %FS/ , the negative sign indicating a decreasing output with increasing tensile strain. In turn, this caused an error of -0.33 % FS for sensors mounted at mid-height on the rotor.

Nominal sensor full scale pressure rating (psi)	25	50	100	250
Perpendicular sens. % nom. F.S. /g	2e-4	1.5e-4	1e-4	5e-5
Transverse sens. % nom. F.S. /g	4e-5	3e-5	2e-5	1e-5

Table 1: Typical acceleration sensitivities for ‘conventional’ devices

The third sensitivity, acceleration sensitivity, is of course more significant in applications where either vibration levels are high, or high centrifugal accelerations are experienced. In aeroelastic applications, there is currently interest in measuring unsteady pressure fields whilst blades are vibrating, excited by the aerodynamics. For the current generation of piezo-resistive sensors, an inertial load experienced by the diaphragm would cause a deflection in that diphragm, and hence an apparent pressure signal would be registered. The size of the effect depends on the acceleration experienced and the full scale pressure range of the device (ie the stiffness of the diaphragm) and is tabulated in Table 1 for the typical sensor in use today.

Whilst centrifugal accelerations in the turbine application are large, they are at least well quantified, and thus this effect may be allowed for in the data reduction process. Alternatively, sensors may be calibrated in situ if the rotor can be rotated in a vacuum. However, in the case of vibrating blades, the levels of acceleration experienced due to the vibration are not so easily quantified, since they will be mode and damping dependent, and indeed more than one mode may be present at a given time. Clearly a pressure measuring device which had no sensitivity to inertial forces would be of some interest to the experimentalist. The next section describes such a device.

3. Acceleration insensitive pressure sensor

In essence, the device is a variant of the technology described earlier, but with two stress deflecting diaphragms mounted adjacently. On each diaphragm, a half Wheatstone bridge is formed using two piezoresistors in series. One piezoresistor of each pair increases in resistance with a positive normal stress to the plane of the diaphragm whilst the other decreases. The two diaphragms are both exposed to the inertial stresses (vibration and centrifugal acceleration induced), but only one is exposed to the pressure to be measured (see figures 2 and 3). The two half-bridges from each diaphragm are electrically coupled to form a full bridge such that for a positive stress applied substantially normal to the diaphragm, the bridge output of one half-bridge will subtract from the other. Thus the signal output is responsive to the pressure as applied to one diaphragm while the signal response to inertial stresses (and indeed any stress other than that due to pressure) applied to both diaphragms is cancelled out. Complete cancellation would of course be dependent on the the two deflecting diaphragms having exactly the same size, thickness, with matching piezoelectric characteristics. The layout of the sensing diaphragm is shown in detail in figure 4, where the two independent half bridges can clearly be seen. In a normal sensor, two additional piezoresistors would be placed in the bottom half of the rectangular aperture, above the stress raising regions created by the presence of the boss (see figure 5), forming the full Wheatstone bridge on one diaphragm. A patent application has been filed which describes in more detail the fabrication of the particular device (Kurtz, 1999a). It will be seen in figure 2, compared with earlier sensors, this generation of device has the piezoresistors mounted underneath the diaphragm (away from the pressurised side) thus protecting them from exposure to corrosive gases. Additionally, electrical contacts to the diaphragm are made by means of the "filled through holes" which are filled with an electrically conductive glass metal paste removing the need for the more conventional gold "ball-bond". This is seen as particularly

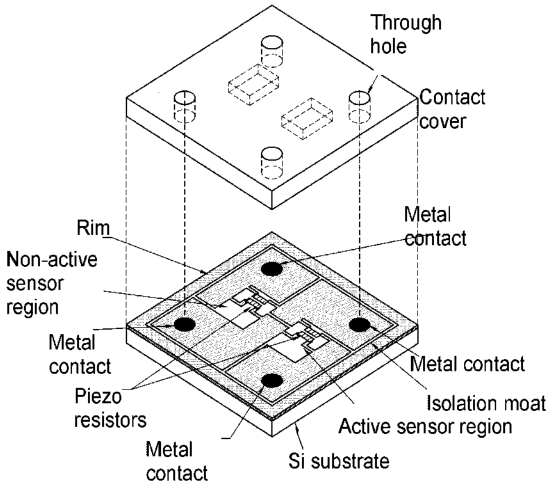

Figure 3: Silicon diaphragm showing piezoresistor sensor disposition, and contact cover by means of which sensor is mounted

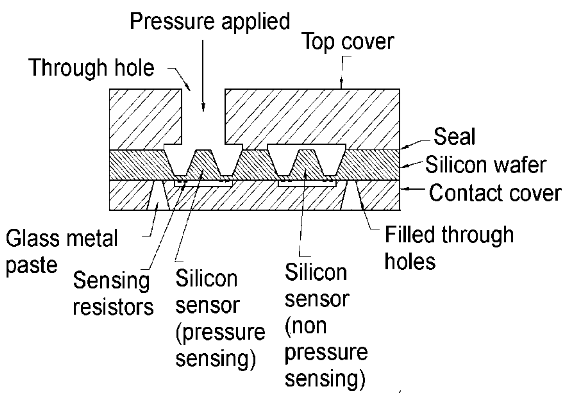

Figure 2: Cross section of 'g-insensitive' pressure sensor, showing top cover, silicon wafer and bottom mounting pedestal

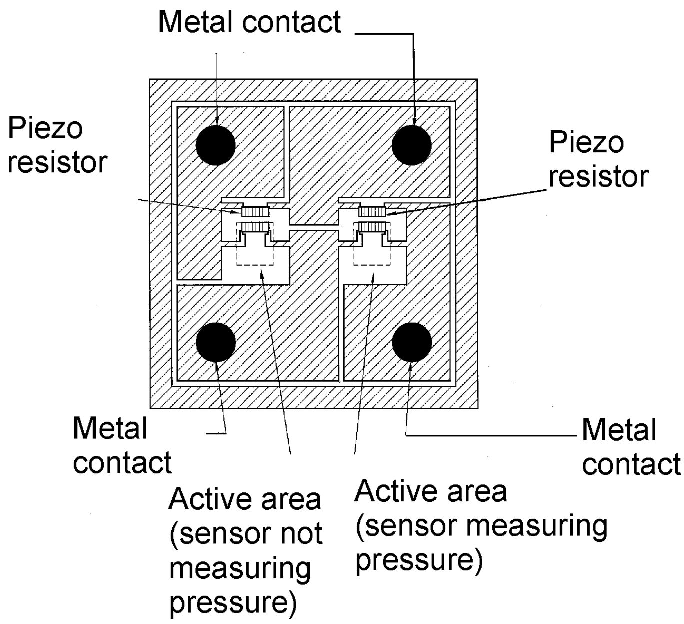

Figure 4: Plan view of silicon chip showing the two adjacent active areas, one only of which is exposed to pressure

advantageous in applications where levels of vibration are high, since the fine gold ball-bond wire is prone to failure at high vibratory levels. Again, this "leadless" technology builds on earlier device development (Kurtz et al, 1999b and Kurtz et al 1976) and will allow the direct attachment of the sensor to a blade surface without the need for any additional connecting leads.

In the present context, the issues to be faced are:

(i) can such a device be constructed?
(ii) does this concept work?
(iii) are the piezoresistive semiconductor coefficients sufficiently well matched between the two half bridges (albeit from adjacent portions of the original silicon wafer) to permit compensation for inertial stresses?
(iv) is the area of "land" between diaphragms sufficient to allow rejection of mechanical stress induced in one from affecting the other?

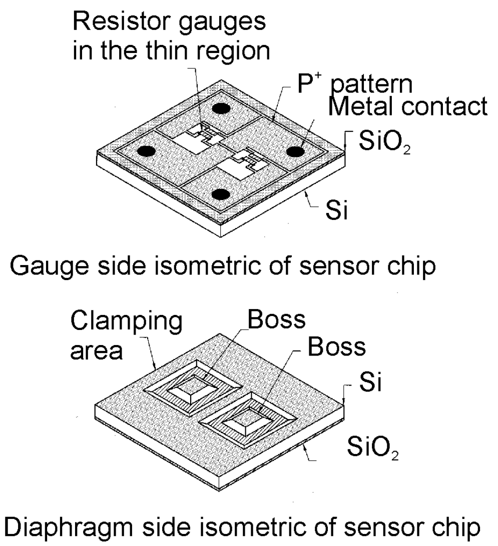

Figure 5: Isometric views of silicon chip showing piezoresistor side and etched diaphragm side

The answer to the first question was quickly provided by Kulite Leonia, where the device was produced within two months of the first discussions. In terms of the second, the normal environmental electrical calibrations were performed in Oxford (Ainsworth et al, 2000). The pressure and temperature sensitivities of six 'g-insensitive' sensors were investigated using a computer controlled environmental chamber. These experiments have enabled the measurement of the following sensor characteristics: span sensitivity, offset sensitivity, fractional slope sensitivity and the temperature coefficient of bridge resistance. The sensors were found to behave in a stable manner over a period of several months. In particular, the new form of electrical contact with the sensor diaphragm ("leadless") appeared to introduce no stability problems.

As far as verification of performance under inertial loadings it was decided to conduct experiments in a spinning rig, described below.

4. Experiments to determine sensor 'g' sensitivity

It was shown earlier in Table 1 that the sensitivity of a conventional piezoresistive pressure sensor to inertial loadings ('g' sensitivity) is not large, and that careful experiementation was going to be required to determine whether this novel sensor design was actually working as intended. It was decided therefore to conduct a datum experiment simultaneously such that the sensitivity to 'g' of a conventional device could be tested at the same time as the new design.

A schematic diagram of the spinning-rig test facility is shown in Figure 6, together with photographs of the rig in Figures 7 and 8. The spinning disk itself is shown in Figure 9. Briefly, the rig consisted of a disk that was rotated by an air-motor, a slip-ring assembly and a sealed containment tank. Services such as air-motor supply and electrical connections were provided through bulkheads. The air pressure within the tank could be varied from 0.02 to 2 atms. The disk had pockets that allowed instrumentation to be positioned close to its tip, with electrical connections being made via copper coated Kapton tracks and miniature wires that passed into the shaft of the rotating assembly (see Figure 9). Extension wires that lay along the axis of rotation connected the instrumentation to a 24 channel slip-ring. The stationary outputs of the slip-ring were connected through a bulkhead to the data acquisition equipment. Sensor output voltage and disk speed measurement signals were recorded by computer controlled

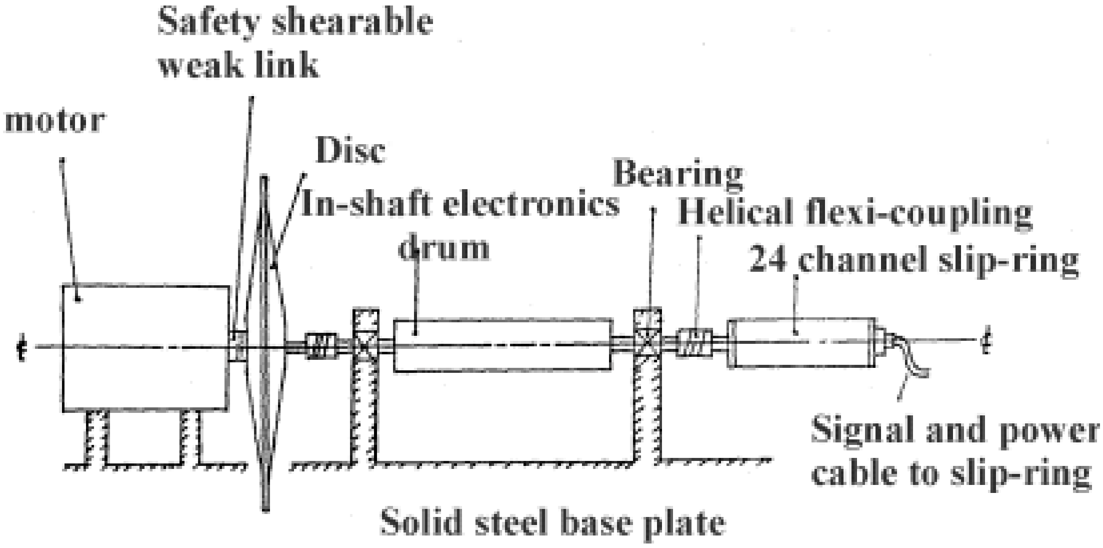

Figure 6: Diagram of spinning rig

Figure 7: Spinning rig ancillary circuits

Hewlett-Packard digital voltmeters at a sample rate of approximately 2 Hz. Run-time data was stored in computer files that were interrogated post-run. A summary of the specification is provided in Table 2.

Disk diameter	0.55	m
Maximum rotational speed	6000	rpm
Maximum radial acceleration	11000	g
Air pressure surrounding disk	0.02 to 2	bar absolute
Slip-ring channels	24	-

Table 2: A summary of the spinning-rig specification.

Figure 8: Spinning rig control and data acquisition system

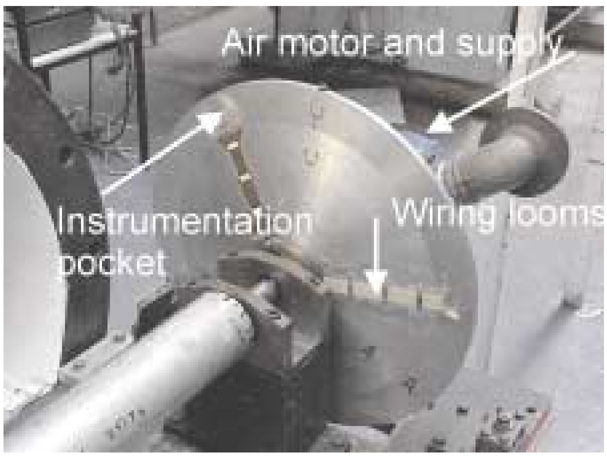

Figure 9: Spinning rig disc - showing instrumentation pockets and wiring looms

A photograph of the location and orientation of the test-sensors is shown in Figure 10. The back surface of the sensors was bonded to a solid surface within the instrumentation pocket. In this configuration, the radial acceleration of the sensors was normal to the sensor surface. In the context of applying these sensors to rotating machinery, this mode would represent a worst case scenario for acceleration effects.

In order to decouple the effects of acceleration and pressure on the transducer output, testing was conducted with low air pressure inside the sealed tank. Experience had indicated that operating at an absolute pressure below 6.6 kPa was sufficient to reduce churning effects within the tank to acceptable levels.

4.1 Experimental results

A typical rotational speed history for a spinning-rig test is shown in Figure 11. The total test duration is approximately 3 minutes, during which time the disk is accelerated from rest to 4000 rpm and then allowed to coast back to rest. The sensor output voltage data are continuously acquired at rate of approximately 2 Hz and this data is subsequently analysed to establish the characteristic 'output versus g' plot for each sensor.

4.2 Piezoresistive pressure sensor results

A measurement campaign was conducted over a period of time with two sensors mounted in the instrumentation pocket simultaneously. The two were of differing types - a 'conventional' sensor and a 'g-insensitive' variant. The idea of this was to allow direct comparison of the output of the two devices under near identical experimental conditions. The 'conventional' device itself was of the 'leadless' type, and thus its diaphragm size and construction was to an extent similar to those in the 'g-insensitive type'. A typical graph of sensor output voltage plotted as a function of acceleration for the 'g-insensitive' sensor (Kulite id. number 3) is shown in Figure 12. This test was conducted at a rig pressure of 5 kPa, being the environmental pressure which could be reached in a reasonable period of time of vacuum pump operation. Note that the offset voltage at this pressure has been subtracted from all the data points. The data exhibits an excellent signal to noise ratio and was obtained at a resolution of 1 V. As can be seen in the graph, the maximum change in voltage during the test is -4 V in the acceleration range 3000 to 5000 g. This represents an acceleration sensitivity of approximately 1e-6 % of full-scale per g.

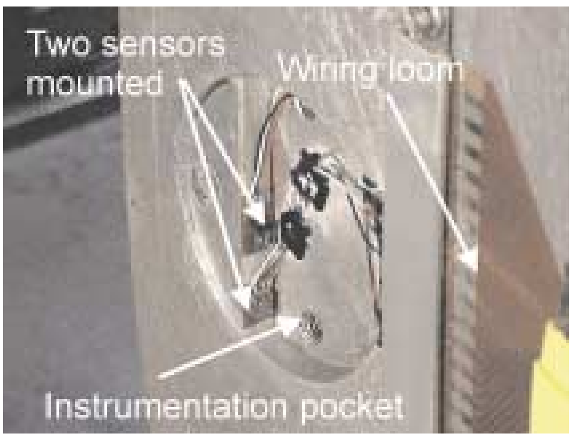

Figure 10: Close-up view of instrumentation pocket, showing two sensors mounted

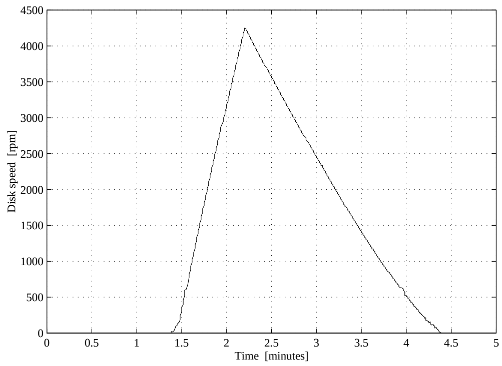

Figure 11: Rotational speed history in typical spinning rig test

Data was simultaneously recorded from a 'conventional' sensor (Kulite id. number 41) and the data from this is plotted together with the data from the 'g - insensitive' device in Figure 13. The data from the 'conventional' sensor shows a linear relationship between sensor output voltage and acceleration. The acceleration sensitivity is 4e-4 % of full-scale per g which, bearing in mind the differences in detail of construction, is in close agreement with figures quoted in Kulite literature and given in Table 1. The corresponding data for the 'g-insensitive' sensor when plotted on this same scale clearly shows the dramatic reduction in acceleration sensitivity associated with this new device.

It should be borne in mind that high fidelity of data acquisition was required to conduct this experiment. Given that the aim was to eliminate 'g-sensitivity', there was also a requirement to verify that this sensitivity had been eliminated. Confidence in

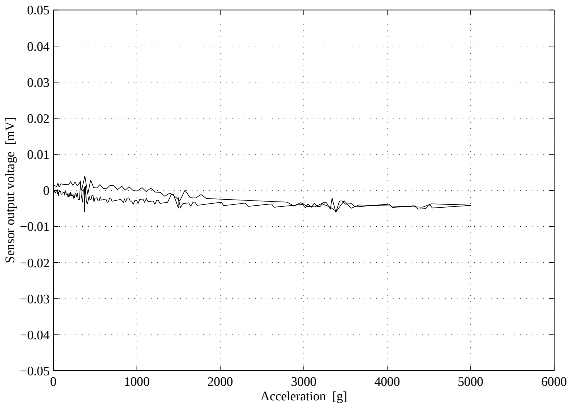

Figure 12: Sensor signal output versus centrifugal acceleration in ‘g’: ‘g-insensitive’ sensor

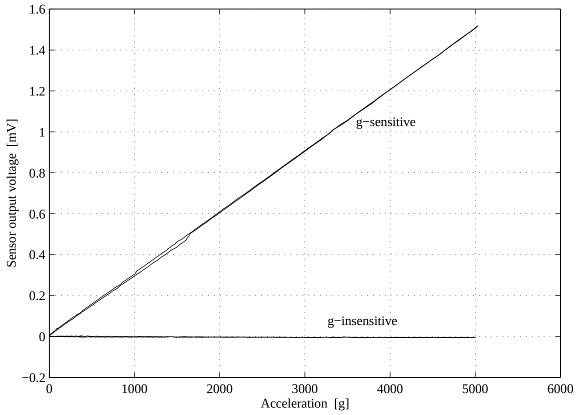

Figure 13: Sensor signal output versus centrifugal acceleration in ‘g’: ‘g-insensitive’ and ‘conventional’ sensors compared

acquired voltages down to the low microvolt level were required and any electromagnetic pick-up would have obscured to result. Being specific, the pressure sensing devices under test had a full-scale output of 100 mV at 25 psi (1.7 bar), thus the resolution of voltage at 1 V was equivalent to 1.7 Pa. It was pleasing to be able to have a ‘conrol’ experiment running simultaneously, in terms of taking data from a ‘conventional’ sensor.

A campaign of measurements over a period of time was conducted, using a number of different sensors, but they all displayed the pattern of behvaiour outline above.

5. Conclusions and Future Work

- A novel ‘g-insensitive’ piezoresistive pressure sensor has been conceived and successfully constructed.
- The electrical performance of the device is comparable to other ‘conventional’ sensors.
- A measurement campaign was conducted in a high ‘g’ environment which demonstrated a very low sensitivity to acceleration (of order 1e-6 % of full-scale per g) .
- Extreme care in experimentation was required to demonstrate this level of performance

Future work will see the application of these sensors to relevant experiments in turbomachinery. This will include their use on blades specifically designed to be excited by aeroelastic forces, and on the tips and hubs of rotor blades, where ‘g’ fields are perpendicular to sensor diphragms.

6. References

Ainsworth, R.W., Dietz, A.J., and Nunn, T.A., 1991, "The Use of Semiconductor Sensors for Blade Surface Pressure Measurement", Journal of Eng. for Gas Turbines and Power, vol 113, p159

Ainsworth, R.W., Miller,R.J., Moss R.W., and Thorpe, S.J., 2000, “Unsteady Pressure Measurement”, Meas. Sci. Technol. **11** pp1055-1076

Epstein, A.L., 1985, "High Frequency Response Measurements in Turbomachinery", VKI Lecture Series 1985-03, Brussels

Kurtz, A.D., and Mallon, J.R., 1976, “High Temperature Transducers and Housing including Fabrication Methods”, U.S. Patent number 3930823

Kurtz, A.D., 1999a, “Vibration Compensated Pressured Sensing Assembly”, U.S. Patent filed 10/12/99

Kurtz, A.D., and Ned, A.A., 1999b, “Sensors for Use in High Vibrational Applications and Methods for Fabricating Same”, U.S. Patent number 5955771