An optical pressure sensor for an aeronautical application using white light interferometry

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ABSTRACT

An optical pressure sensor for measuring hydraulic pressure in an aeronautical application is described. It is based on interferometry with low-coherence light coupled with single mode fibre. The design uses an anisotropically etched silicon diaphragm, electrostatically bonded to a borosilicate glass insert, mounted in a titanium body.

Keywords: Pressure, silicon, optical, white-light interferometry, hydraulic, micromachined

1. INTRODUCTION

This work was part of the FLAPS collaborative project, for which the objective was to demonstrate an optical sensor system using more than one type of sensor. The demonstrator included a hydraulic pressure sensor, which is the subject of this paper, to be installed on an Airbus landing gear. The chosen sensing principle was low-coherence light interferometry with single mode fibre.[1] The Fabry-Perot resonant gap was 80μm reducing by 10μm at a full scale pressure of 200 bar. The error needed to be within ±2% over the entire temperature range of -60 to +80°C.

2. DESIGN AND CONSTRUCTION

2.1 Sensing element

The geometry of the silicon diaphragm and the glass insert were designed using the ANSYS Finite Element Analysis package with axisymmetric models. At first a simple model was used to adjust the dimensions to give the required 10 μm deflection at 200 bar pressure, without causing excessive stress. Note that, in contrast to normal strain-gauge based pressure sensors, we needed to achieve a certain deflection rather than level of strain. The diameter and thickness have to be increased in order to accommodate larger deflections for a given maximum stress level. This initial work showed that we needed a diaphragm about 9mm diameter and 1mm thick.

The model was then refined to add the complete glass support. This has to provide an optical window to the inside of the package, which means that it will form part of the pressure containment and will be subjected to high levels of stress. The design is shown in Fig. 1 where it can be seen that there is a circumferential groove in the glass to provide stress relief.

A small number of sensors were made and tested. The optical output was as intended but the sensors failed when subjected to the highest pressure. On examination we found that the silicon diaphragm had broken away from the glass, leaving fracture damage particularly round the edge, indicating that the silicon-to-glass bond was not perfect at this edge. A modified finite element model was made in order to work out what was happening and it was clear from this that even the smallest unbonded area at the edge will produce a stress riser. Fig 2 shows how the centre of the diaphragm is pushed in by the pressure, the outer rim is twisted and the outer edge is put in tension. There is also a severe stress concentration on the inner edge, which is less critical because it is in compression.

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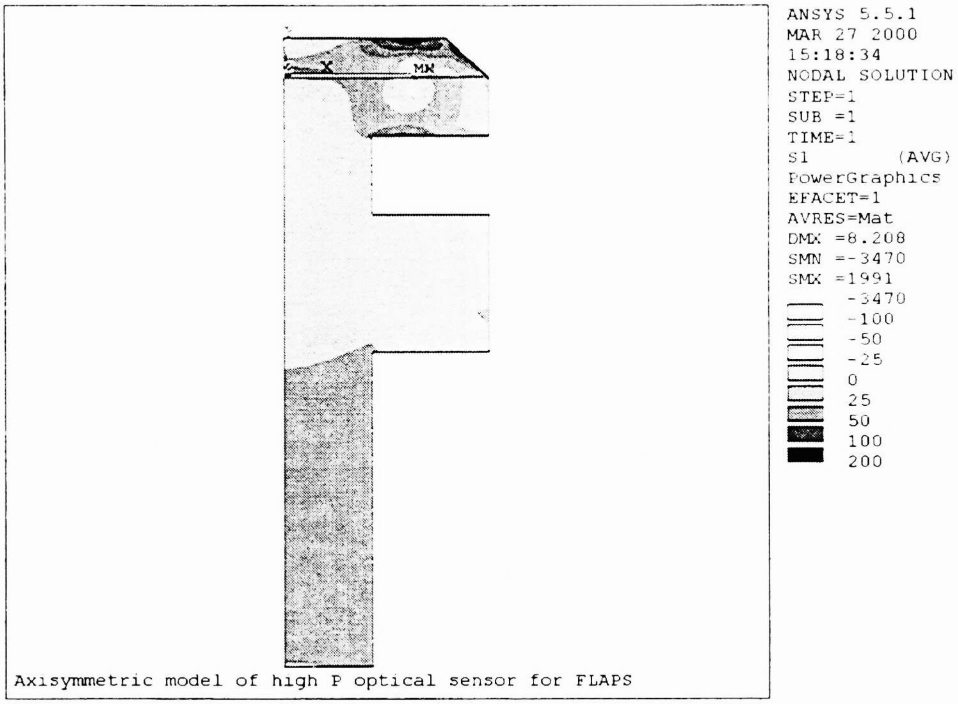

Fig.1 Axisymmetric finite element model showing first design of silicon diaphragm on a borosilicate glass base

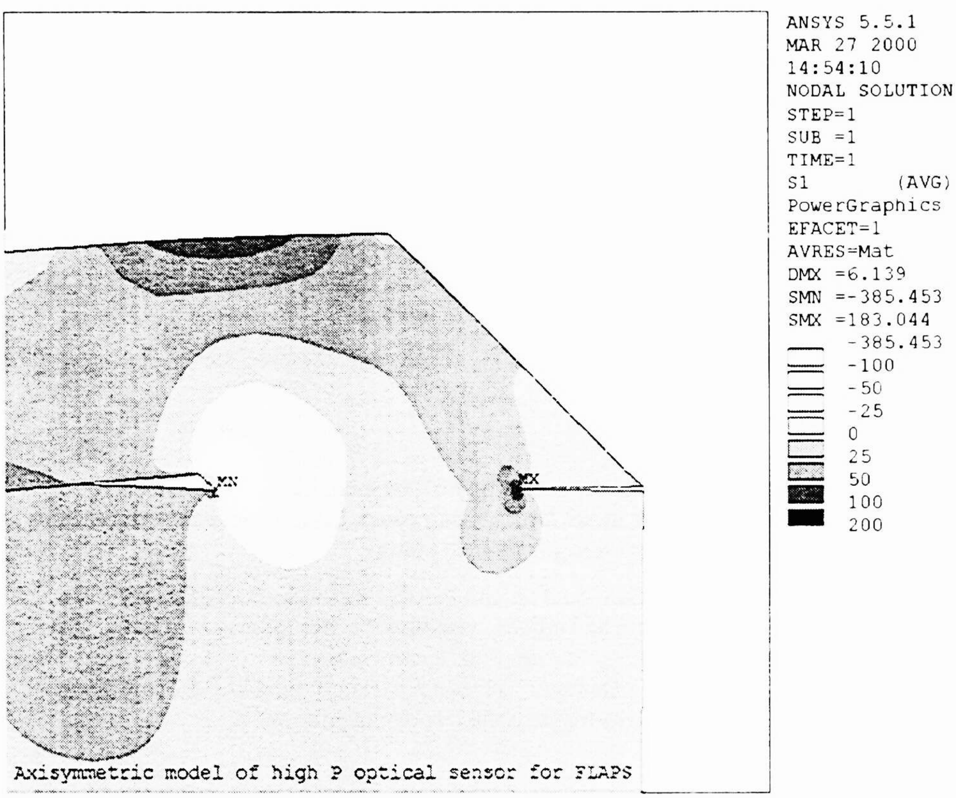

Fig. 2 Finite element model showing a tensile stress concentration caused by imperfect bonding at the edge of the diaphragm

The profile of the diaphragm edge was modified, the most important change being the addition of a "brim", which has the effect of moving the region in tension to a corner formed by etching the silicon. The inner edge was also modified with the addition of a small lip formed by a boron etch stop. These features are shown in Fig. 3.

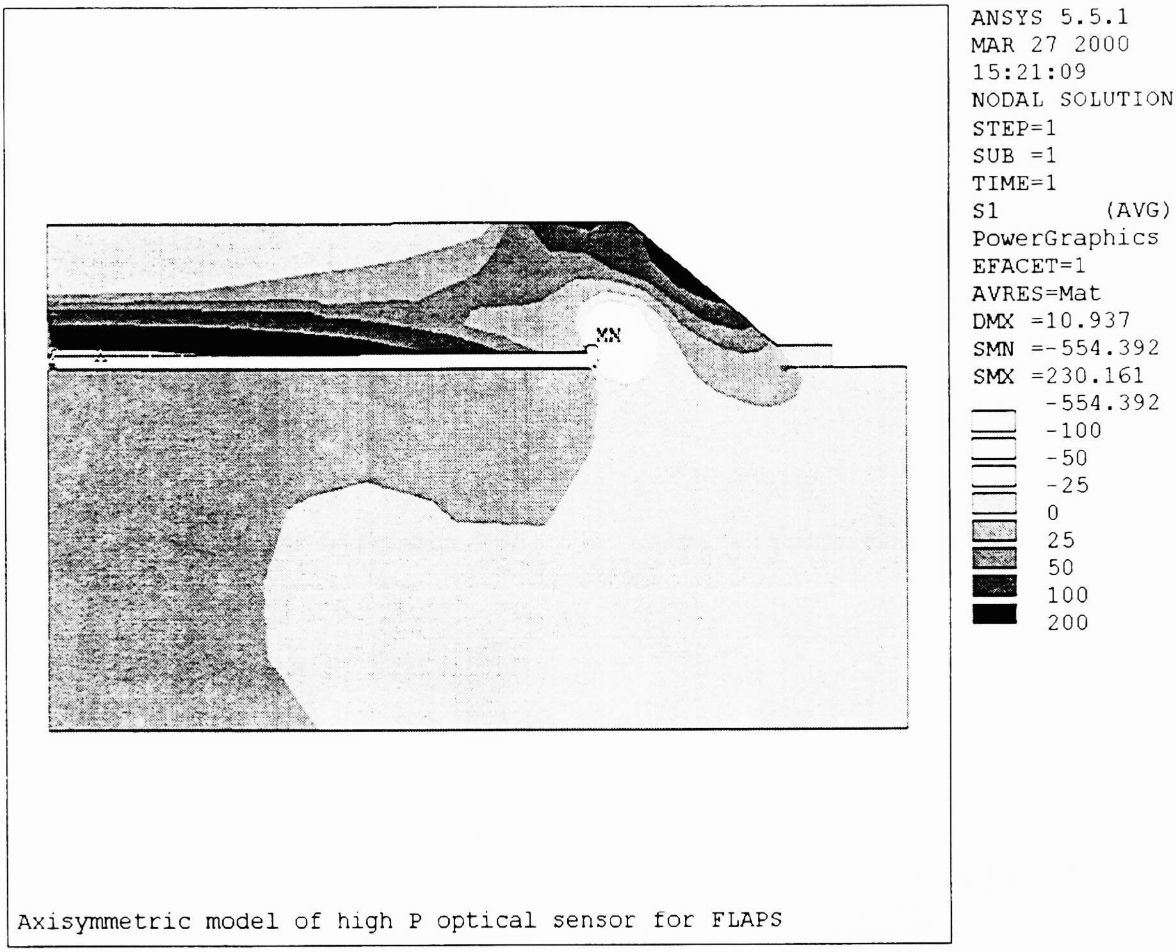

Fig. 3 Finite element model of the diaphragm edge modified to move both the tensile and compressive stress concentrations away from the bond

The approximately round shape is obtained by compensating for the anisotropy of the etch. The silicon has a <100> orientation, the etch is KOH/IPA, and the fabrication was done in the Druck clean room. Figs. 4 and 5 show both sides of a complete wafer with a number of diaphragms. The diaphragms are separated by sawing.

The borosilicate glass inserts were made by a subcontractor. Individual silicon diaphragms were bonded to the glass inserts by electrostatic bonding in a vacuum. The glass insert, with attached silicon, was bonded into the titanium body. The titanium front end, which incorporates the required pipe coupling, was electron beam welded on to the body. Fig. 6 shows the two parts of the metal package and the silicon/glass sensing element. The construction of the body follows normal Druck practice for high-pressure sensors. The titanium parts were made in the Druck machine shop.

2.2 Optical interface

The light from the fibre is collimated by a GRIN lens. The beam has to be normal to the inside face of the diaphragm with considerable accuracy in order that the returning beam is focused back into the fibre. The first scheme was to use the flat external end of the glass insert to provide a mechanical datum. The glass part had been made with the two end surfaces accurately parallel. An accurately machined ferrule on the front end of the GRIN lens was clamped against the flat glass surface which was intended to hold it precisely normal. In practice, this did not work. The first attempt was mis-aligned and it became clear that this arrangement was not sufficiently rigid, so that even small forces on the far end of the GRIN lens could spoil the alignment and cut off the transmission.

The scheme which was used in the project demonstrator had a back end which located the GRIN lens with a set of adjusting screws. The complete sensor assembly is shown in Fig. 7.

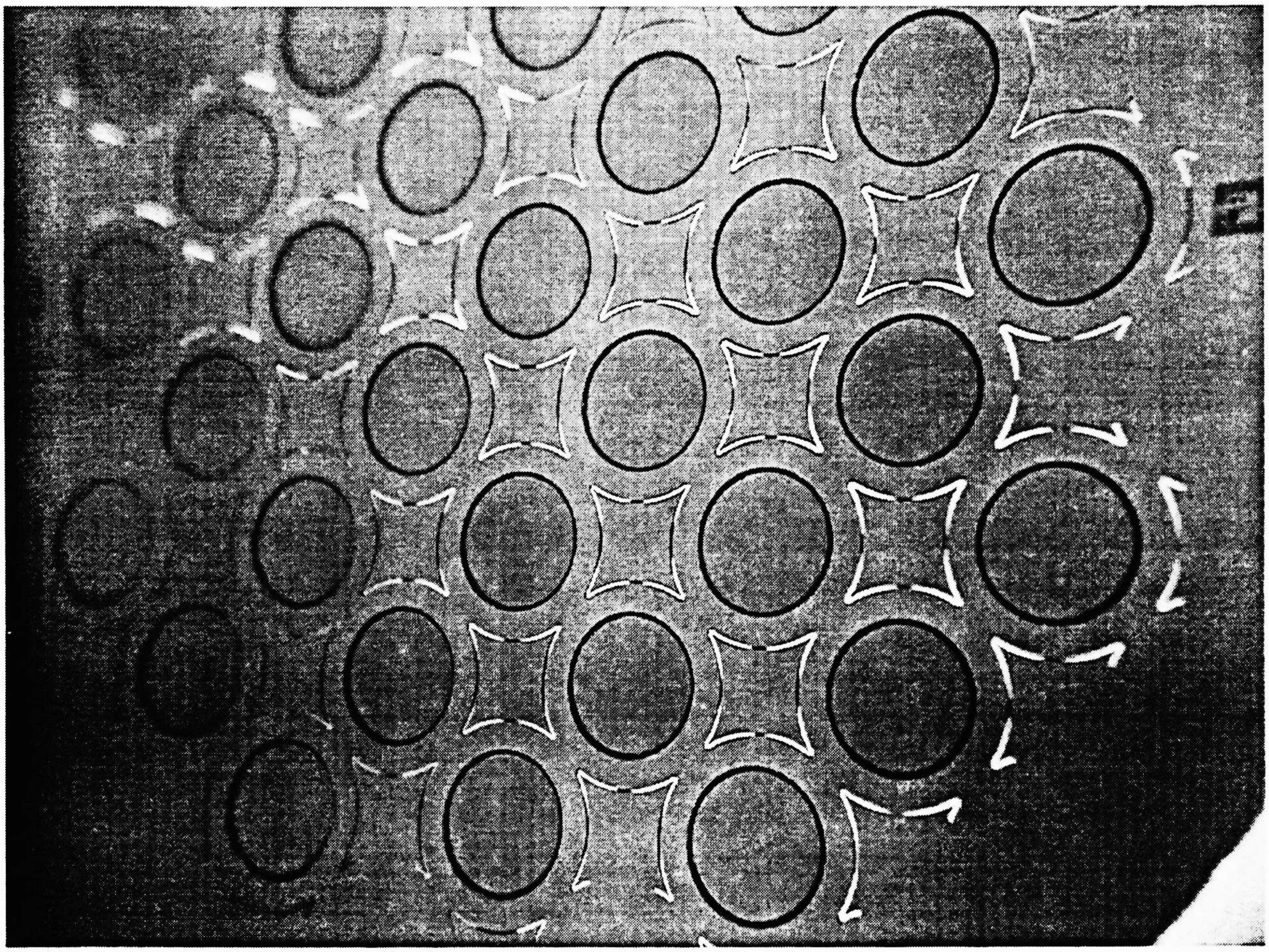

Fig. 4 Internal side of diaphragms on a silicon wafer

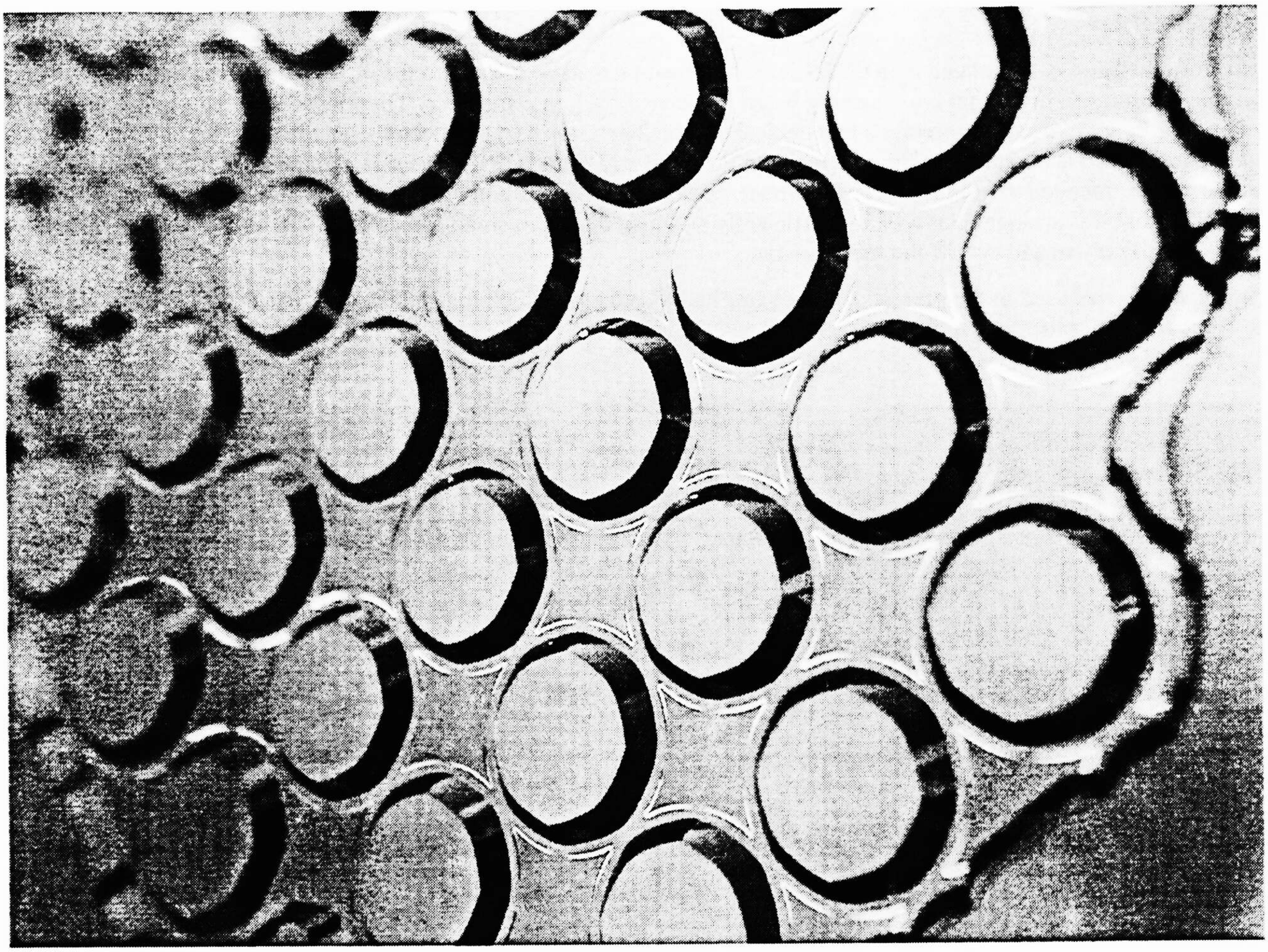

Fig. 5 External side of diaphragms on a silicon wafer

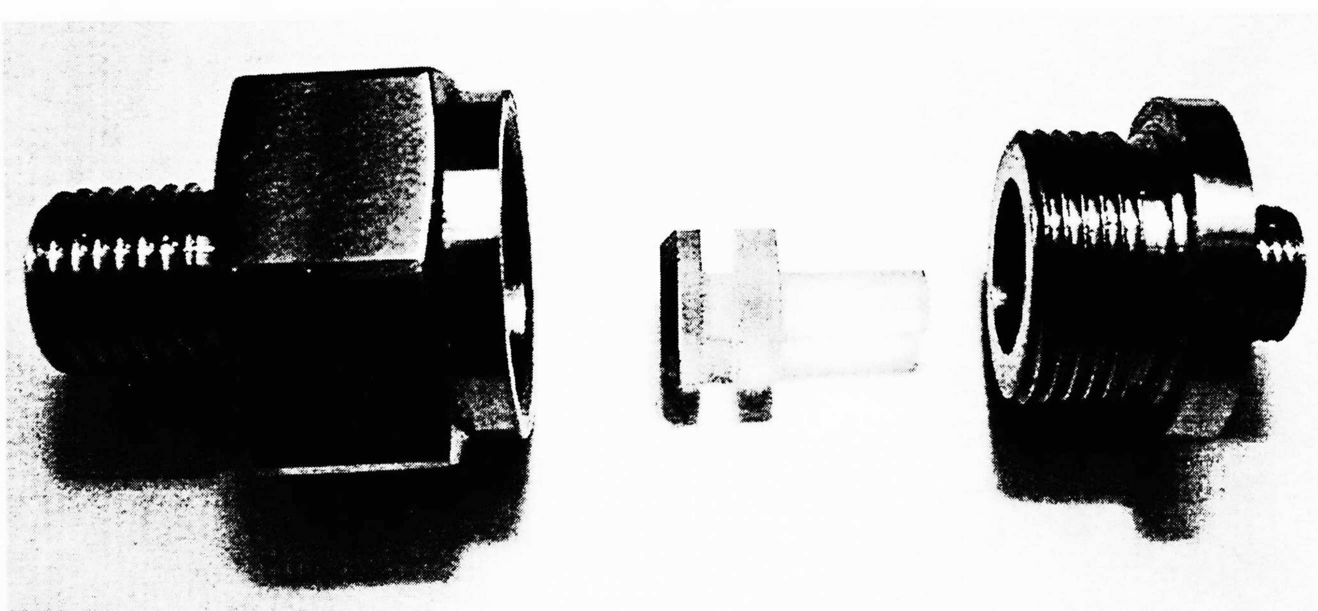

Fig.6 Silicon/glass sensing element in between the two halves of the titanium package

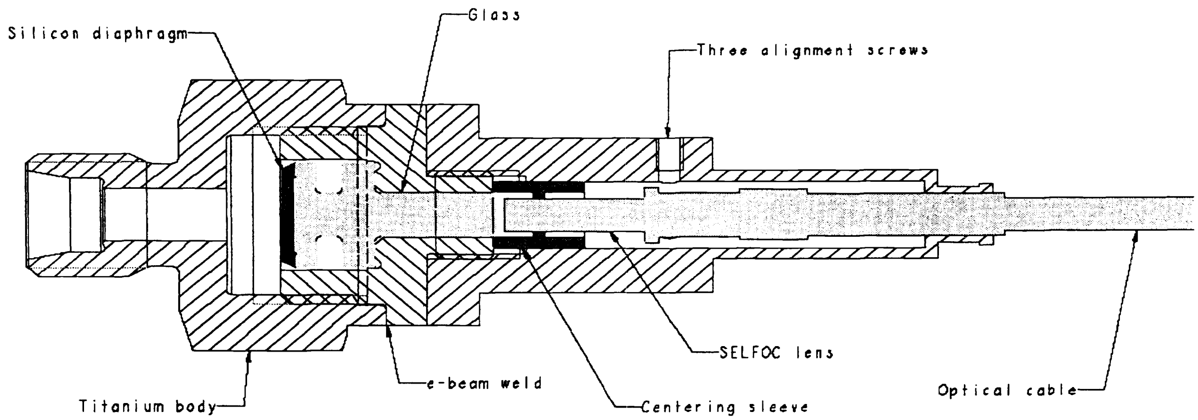

Fig. 7 Cross-sectional diagram of the complete assembly

3. RESULTS

The sensor was calibrated against a dead weight tester at a range of temperatures between -40 and +80°C. Fig. 8 shows the deviation from a straight line, fitted to the 20°C data. The maximum deviation was less than 0.6%. Hysteresis was less than 0.1%.

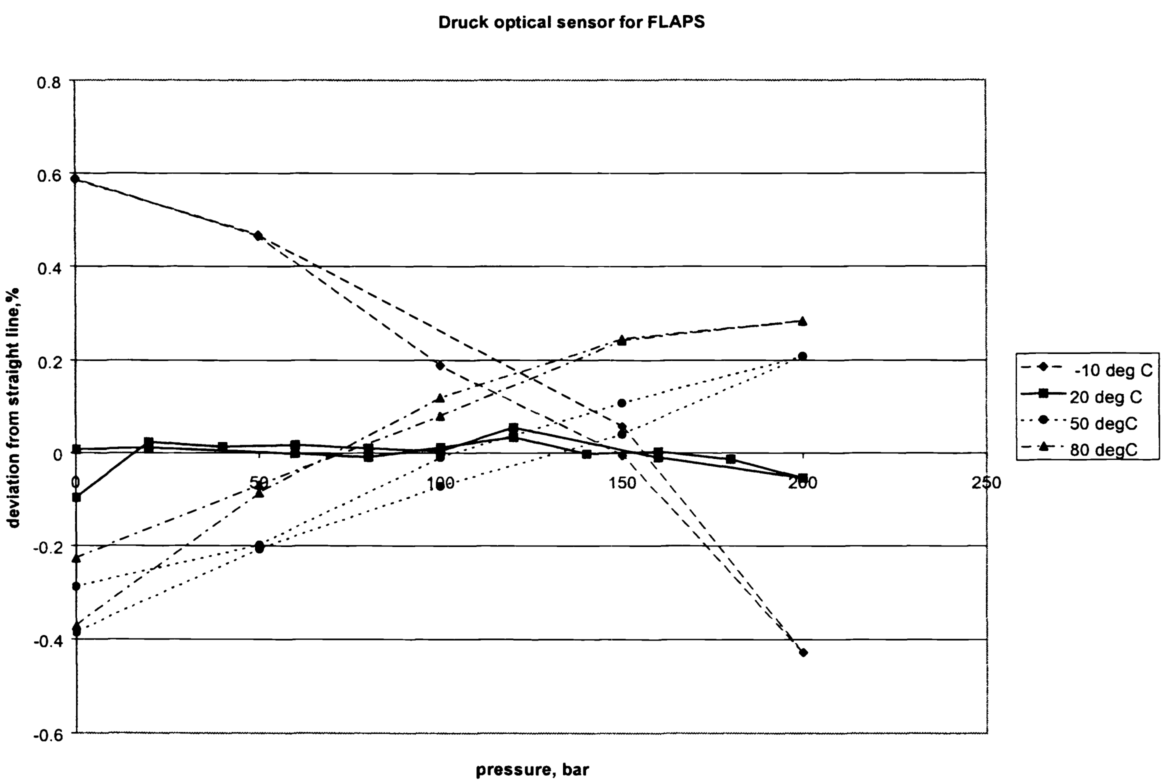

Fig. 8 Calibration of a sensor against a dead-weight tester

4. CONCLUSION

An optical pressure sensor was developed as part of the FLAPS collaborative project to measure hydraulic pressure in a demonstration aeronautical application. It is based on interferometry with low-coherence light coupled with single mode fibre. The design uses an anisotropically etched silicon diaphragm, electrostatically bonded to a borosilicate glass insert, mounted in a titanium body.

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