Zero Mass, Packageless and Non-Invasive Pressure Transducers

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ABSTRACT

Mass is a major driver for future spacecraft, and missions exposed to high radiation levels (i.e. Europa Orbiter) present even more challenge. Non-invasive pressure measurement techniques that enable the accurate determination of pressures within a propulsion system will be described and their performance reviewed. The feasibility of low cost, extremely low mass, robust and non-invasive pressure transducers capable of less than 0.25% error bands also have broad appeal for a number of terrestrial pressure measurement applications. Such 'hoop strain' measurements offer the advantage over a typical pressure transducer that no penetration of the feed system tubing is required. This contributes to the reduction in system mass, in addition to the elimination of feed system welds requiring X-ray and leak checks.

BACKGROUND

Conventional flight pressure transducers for spacecraft (S/C) applications typically weigh over 0.25 kg, cost $10-20k per unit plus $50-100K of non-recurring costs, have lead times of 9-12 months, are susceptible to reliability problems of both long-term drift and zero shift, and their electronic parts are susceptible to radiation induced failures.

While strain gages have been used for years to measure pressure within pressurized systems, the only known application of strain gage technology for spacecraft pressure measurements is their use on external flat surfaces of batteries. In this study, internal system pressure is measured by sensing changes in the strain of the tubing outer wall. Such 'hoop strain' measurements offers the advantage over a typical pressure transducer that no penetration of the feed system tubing is required. With the emphasis of future S/C clearly headed in the direction of Faster/Better/Cheaper, there is a real window of opportunity for a micro technology alternative to the conventional pressure transducer.

The micro strain gage applications investigated were piezo resistive gages sputtered directly onto the outer walls of stainless steel and titanium tubing. Traditionally radiation susceptibility is ameliorated by either a strenuous parts screening program, which translates into additional cost, or the addition of radiation shielding, which translates into additional mass. In the 'hoop strain' implementation there is no 'incorporated' electronics requiring shielding.

DETAILED APPROACH

Micro-strain foil gages (considered to be mature technologies), applied to the exterior tubing wall with adhesives, provides non-invasive hoop strain measurements of pressure differences between the inside and outside of the tube. One problem inherent in building strain gaged tube pressure transducers is that strain may be produced not only from the applied pressure, but due to bending, torsion, or axial loads that may be imposed on the tubes. The emphasis of this research was to develop techniques for the intimate attachment of piezo resistive micro-devices to the circumference of tubes and to develop a design that minimize the response to mechanically induced strains, other than those produced by changes in pressure. Orienting two strain gages at approximately 61.3 degrees to the tube axis (optimum angle of orientation is solely a function of Poisson's ratio for material) and wiring them into opposite arms of the Wheatstone Bridge reduced sensitivity to bending or tortional strains for approximately 83% of the hoop strain component. The tube surface experiences no compressive strain for 'hoop' strain measurement necessitating bridge completion resistor placement on a separate zero strain element. Figure 1. illustrates this arrangement where unstrained tube segments were fabricated from the same but larger diameter tube stock and spot welded to the tube. Figure 2. presents a drawing of the preferred embodiment that consists of a flat surface design that provides compressive (actually neutral) strains on the surface of the tube as well as pressure induced tensile strains. This design has the benefit of much closer thermal time constants between gages and thus smaller thermal transients within the bridge circuit.

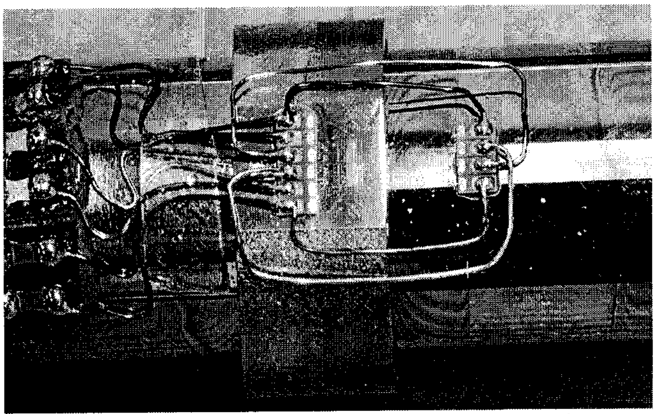

Figure 1. *Circumferential 'Hoop' Strain Transducer*

The application of gages by sputtering directly to the tubing wall eliminates potential problems associated with slipping, thermal expansion, delamination and, for spacecraft applications, out-gassing. To increase accuracy, temperature measurements are taken to compensate for any thermal disparities, and individual calibrations of each assembly will accommodate any discontinuities in wall thickness, gage resistances and material properties.

Standard thin wall stainless steel and titanium tubing in sizes of 0.375 and 0.50 inch outside diameter were polished to a high degree prior to treatment. Sensors were fabricated on both materials by sputtering on a continuous thin film of piezoresistive nickel-chromium and subsequently forming the strain gage grids by laser cuts in the film (Figure 3). An encapsulating insulator was then sputtered over gages and wiring – the ultimate in 'packaging' simplicity.

TEST SET-UP

The test system consisted of a computer-controller Ruska precision pressure standard (less 30 PPM of full-scale pressure), an environmental chamber, precision ratiometric A/D module (non-linearity of 0.003% and a resolution of 0.01 microvolt/volt) and a multiplexed HP 37904A resistance meter. Four tubes were supported off a manifold that kept the weight off of the tubing and prevented any torque or mechanical loading of the sensor

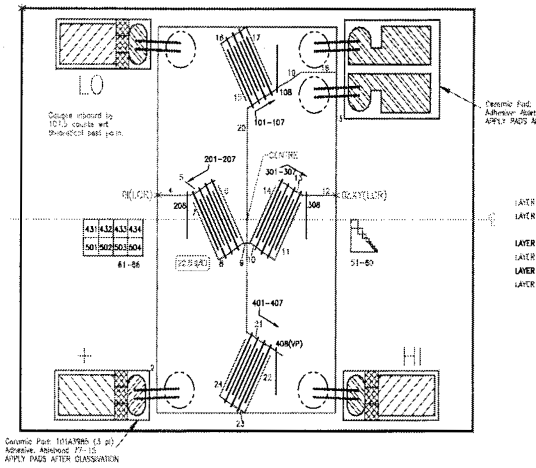

Figure 2. *Bridge Configuration*

TEST RESULTS

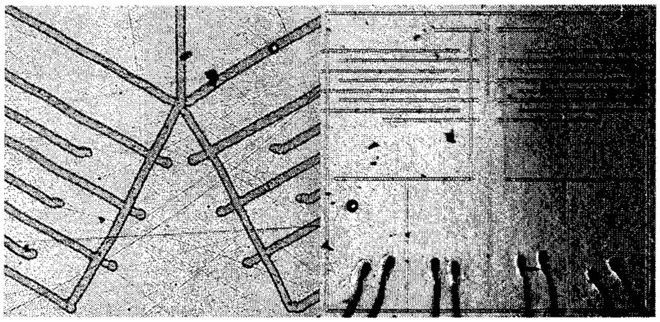

Figure 3. *Piezoresistive Laser Cut Gages*

The deposited gages exhibited large resistance mismatches, with individual gages varying as much as 100 ohms from nominal values of 3000 ohms. This has implications on effective cancellation of undesired strain components and on the uncompensated thermal output, as does the relatively high thermal output characteristics of the deposited gages (compared to the foil gages). Figures 4 and 5 show thermal output results from stainless and titanium tubes. Test results established that thermally equilibrated calibrated stainless steel sensor errors of 0.2 to 0.5% were attained with the bridge completion resistors attached to a tube segment that was welded to the tube, and calibrated titanium sensor errors of 0.04 to 0.16% were attained. Figure 6 presents the influence of thermal transients between sense and completion gages. The thermal transient time constants are reduced by moving the bridge completion resistors to the tube (see Figure 3). Figure 7 present the equilibrated strain/temperature relationship for such a titanium sensor. The thermally equilibrated calibrated stainless steel sensor errors of 0.125 to 0.134% were attained with the bridge completion resistors on tube segment and calibrated titanium sensor errors of 0.032 to 0.061% were attained. These results established the feasibility of producing transducers with performance levels of better than the required 0.25% accuracy.

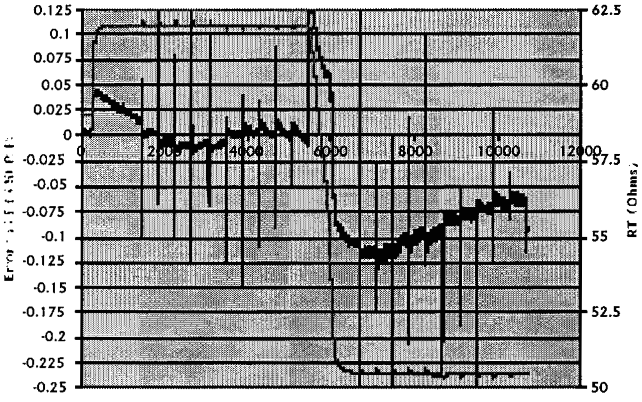

Figure 6. *Pressure Temperature/Strain Estimation Errors*

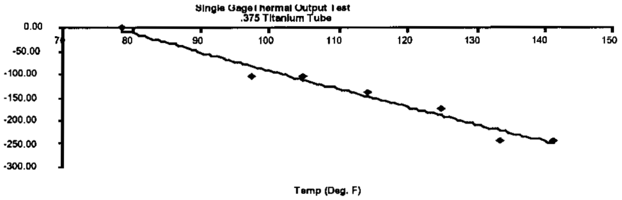

Figure 4. *Thermal output for 0.375" titanium tube*

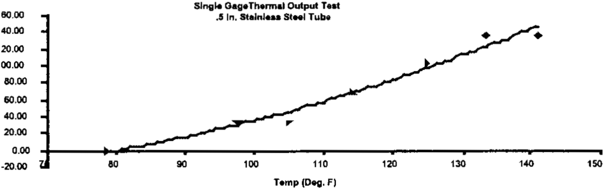

Figure 5. *Thermal output for 0.5" stainless steel tube*

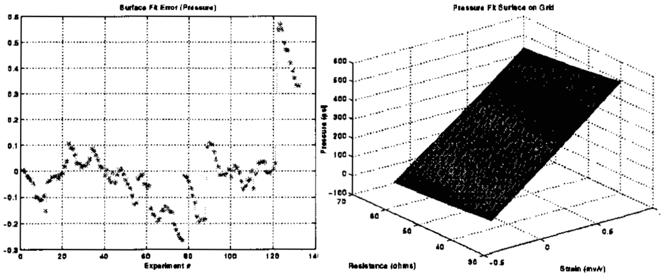

Figure 7. *Model Errors and T/S Surface For Titanium Sensor*

CONCLUSIONS

Nickel-Chromium thin-film gages were successfully deposited on both circumference and machined flats of both stainless steel and titanium tubes with diameters of 0.375 and 0.5 inches. These parts exhibited higher thermal output characteristics than the foil gage transducers bonded to the tube walls. There is no simple means of reducing the thermal output of the deposited gages, although gage self-heating may be minimized by lowering excitation voltage, adopting pulsed excitation of short duty cycle, or using higher resistance gages. However, since pressure measurements of primary interest in propulsion applications are 'steady-state', thermal equilibration delays are not an issue and temperature (equilibrated) effects may be compensated for digitally. The thermal response times of machined tubes is acceptable but may be improved by both removing the protective cover or by improved matching of gage resistances. Thermally equilibrated digitally compensated parts performed with better than a +/- 0.25% error band. Hence, a **zero mass, packageless, radiation tolerant and non-invasive pressure transducer has been produced that is clearly superior to conventional pressure transducers.**

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