Commercial Opportunities for 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. Low cost, extremely low mass, robust and non-invasive pressure transducers also have broad appeal for a number of terrestrial pressure measurement applications involving extremely reactive fluids, hygienic networks, arduous environments and unobstructed flow. Applications in aviation, automotive, medical, food processing and fuel cell sectors will be discussed.

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 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 an advantage over a typical pressure transducer because 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 broad appeal of low cost, extremely low mass, robust, non-invasive and accurate pressure transducers will be discussed for a variety of terrestrial pressure measurement applications.

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 circumferences of tubes and to develop a design that minimize the

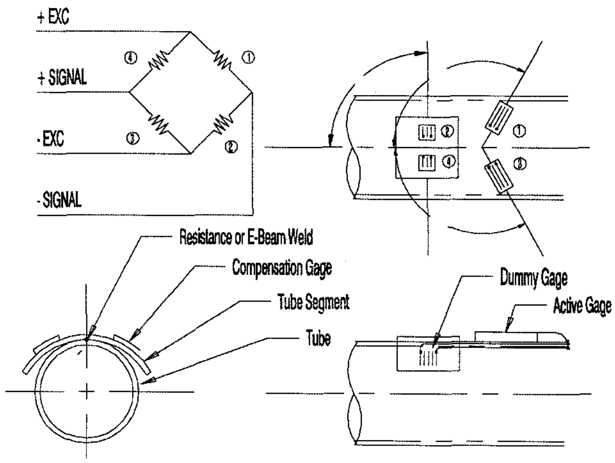

Figure 1 *Hoop Stran Measurement*

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 (Figure 1). The tube surface experiences no compressive strain for 'hoop' strain measurement necessitating bridge completion resistor placement on a separate zero strain element.

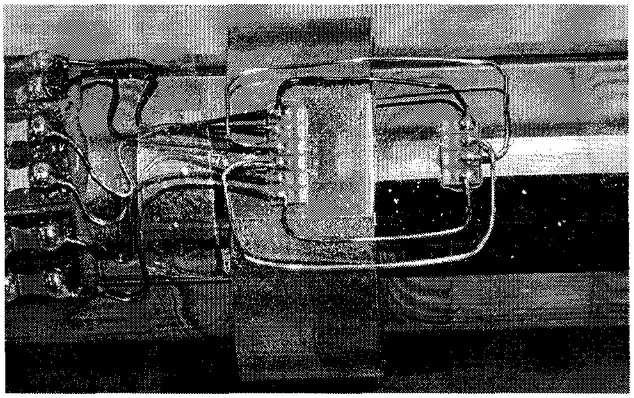

Figure 2. *Circumferential 'Hoop' Strain Transducer*

Figure 2. illustrates this arrangement where unstrained tube segments were fabricated from the same but larger-diameter tube stock and spot welded to the tube. Figure 3. presents FEA strain contour plots for a preferred embodiment (Titanium tube) that consists of a flat surface design that provides 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.

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

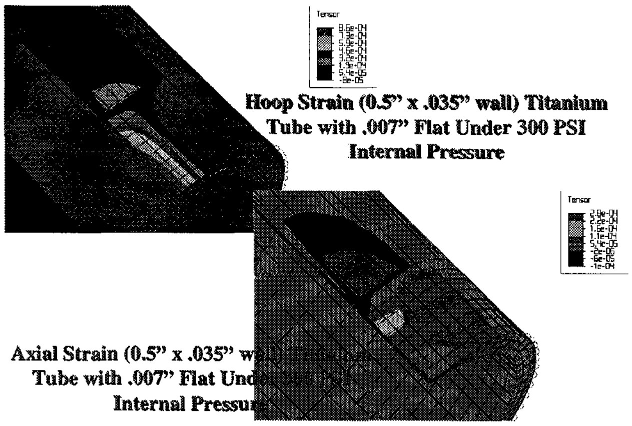

Figure 3. *FEA strain contour plots*

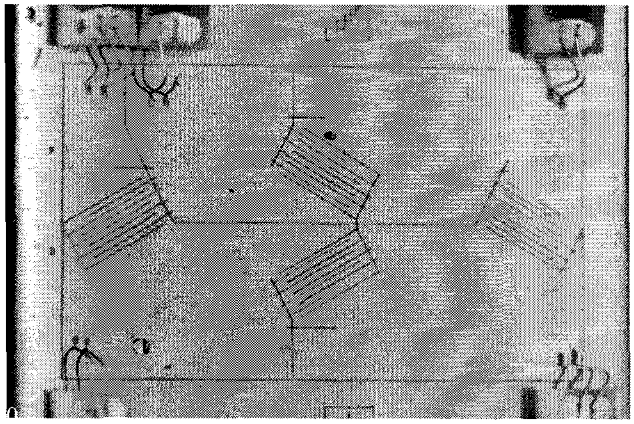

Figure 4. *Piezoresistive Laser Cut Gages*

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 (Figures 2 and 4). 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

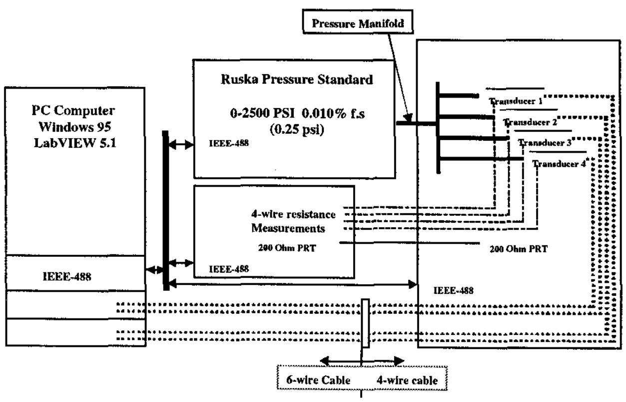

Figure 5 *Metrology system*

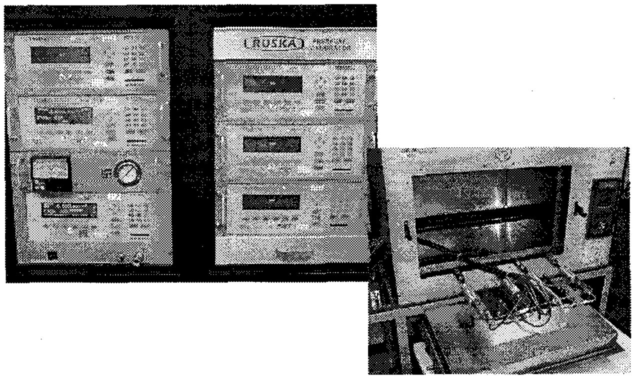

Fig. 6 *Characterization and calibration equipment*

(less 30 PPM of full-scale pressure), an environmental chamber (Figure 6), Interface (card in PC) precision ratiometric A/D modules (non-linearity of 0.003% and a 1 year manufacturer spec. of +/- 0.018 mV/V) with an indicated resolution of 0.011 microvolt/volt and a 4-wire multiplexed HP 37904A/34901A resistance meter (+/- 0.01 % rdg + .004% f.s. = +/- 0.011 Ohm at 70 Ohms) with a measured 3-sigma distribution of less than 0.001 Ohm.

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 6).

TEST RESULTS

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

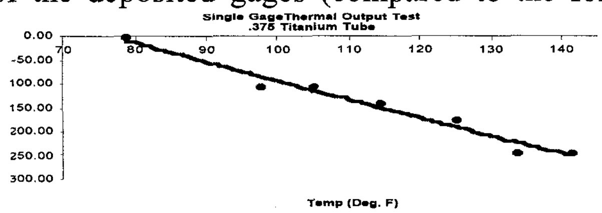

Fig. 7 *Thermal output for 0.375" titanium tube*

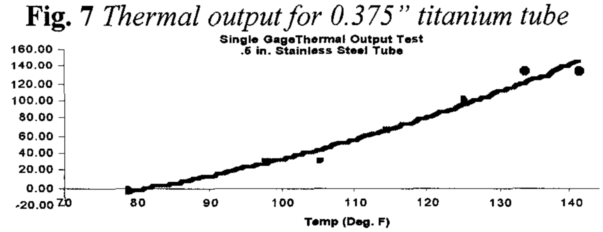

Fig. 8 *Thermal output for 0.5" stainless steel*

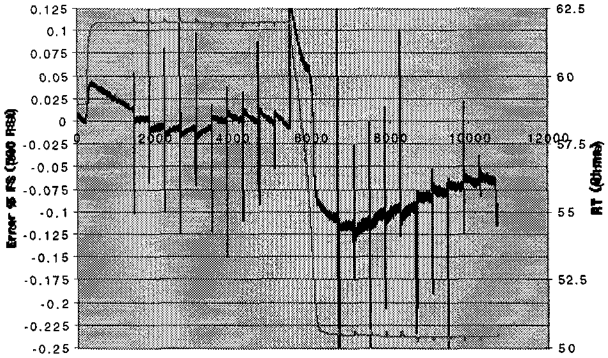

Fig. 9 *Pressure Temperature/Strain estimation*

gages). Figures 7 and 8 show thermal output results from stainless and titanium tubes. Figure 9 presents the influence of thermal transients (adiabatic temperature changes in gas due to changes in pressure) between sense and completion gages. The thermal transient time constants are reduced by moving the bridge completion resistors to the tube (see Figures 3 and 4). Figure 10 present the equilibrated strain/temperature relationship for such a Titanium sensor. The thermally equilibrated calibrated stainless steel sensor errors of 0.02 to 0.13% were attained with the bridge completion resistors on tube segment and calibrated titanium sensor errors of 0.01 to 0.06% were attained. These results established the feasibility of producing transducers with performance levels of better than the required 0.25% accuracy.

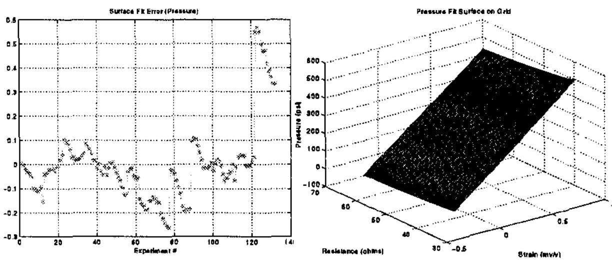

Figure 10 *Model Errors and Temperature/Strain surface for Titanium sensor*

CROSS TALK

Instrumented tubes were subjected to a series of mechanical load tests to determine the sensitivity of the pressure measurement to axial load, moment loading in two orthogonal planes, and torque. In order to have some basis for comparison of the bridge output, the measured output for a given mechanical load is scaled to the load that would produce a principal strain equal to the hoop strain (maximum principal strain) produced under the rated pressure loading for the tube.

For the smallest diameter (0.375") and thinnest walled (0.020") Stainless Steel tube the cross talk for axial load {248 lbs.}, bending 0^0 {21 in-lbs.}, bending 90^0 {21 in-lbs.}, and torque {42 in-lbs.} were 1.1, 2.2, 0.2, 1.8 percent of rated output (3000 PSI) respectively. The data indicates that the cross talk produced by mechanical loading strains are at worst a few percent of the sensitivity to pressure induced strains. Contributing factors are gage placement with respect to the tube centerline, the angle of the gages to tube centerline, gage geometry symmetry, gage resistance symmetry and actual Poisson ratio of material. In practice, if the mechanical loading is constant, the only effect is a shift of zero balance. The moment or torque loading of the element may be reduced to the degree necessary by adding a bend in the tube before and after the instrumented section and/or mechanically supporting the tube.

ATTRIBUTES

Low mass, robustness, radiation tolerance and non-invasion are the attributes required for future spacecraft propulsion systems. Traditional foil strain gages are stressed through compliant backing and adhesive while thin film gages are stressed through thin sputtered dielectric coatings that are in intimate contact with tube surface (and piezoresistive film) at the molecular level. Hence thin film gages have less propensity for delamination and creep and superior thermal and mechanical (stress transfer) coupling with tube surface. The intimate coupling increases 'gage factor', simplifies thermal coefficients, reduces thermal time constant and diminishes long term drift and zero shift. The transducer 'packaging' and encapsulation consists of a thin sputtered insulation (dielectric) layer over the gages and bridge wiring which eliminates 'out gassing' and the propensity for any chemical reaction with environment. The high dissociation temperatures of dielectrics and piezoresistive films enables operation at high temperatures and the thin intimate structure extend operation down to cryogenic temperatures.

Conventional pressure transducers are coupled to fluid networks through threaded journal fittings and seals and at least one surface of pressure stressed diaphragm is exposed to contained fluid. Alternatively, the 'hoop strain' pressure transducers, particularly when tube is welded into fluid network, has no fittings or seals and no diaphragm (aside from tube wall itself). From a chemical perspective this 'non-invasive' attribute eliminates reactive chemical corrosion of materials, such as fittings, seals and diaphragm, and in quiescent voids in diaphragm cavity and around seals and internal journal threads. From hygienic and toxicity perspectives this 'non-invasive' attribute eliminates sites for materials to stagnate and ferment and enhances thorough 'cleaning' of network. From a rheological perspective this 'non-invasive' attribute eliminates erratic dynamics; reduces propensities for cavitation and 'frothing'; and enables the unimpeded transport of pulps, slurries, viscous fluids and biological materials. From a mechanical prospective the transducer is essentially part of the tube (virtually no mass) with no protrubences which enables the sustenance of extreme shock and vibrational loads and provides immunity from impact fracture.

COMMERCIAL SECTORS

Reactive Chemicals

- Processing fluids and vapors for electronics and MEMS foundries
- Fuel cell agents
- Propellant handling
- Chemical reactors

Medical and Food processing

- Dialysis networks
- Heart-lung oxygenator systems
- Respirator networks
- Pathology instruments
- Pulps and slurries
- Essence concentrates and beverages

Aviation, Agricultural, Automotive, Construction

- Hydraulic brake, suspension, actuation and transmission networks
- Fuel flow and aspiration regulation
- HVAC and refrigeration networks
- Slurry transport

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. Thermally equilibrated digitally compensated parts performed with better than a +/- 0.125% f.s. error band over a -25^0 to 65^0 C temperature range and with acceptable levels of mechanical cross talk. The attributes of thin film non-invasive pressure transducers were discussed and comparisons made with conventional pressure transducers. The domains of superiority were then explored and commercial sectors identified. Capitalizing on the commercial opportunities for this technology involves selection of specific application and tailoring the design and production equipment for economic fabrication.

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