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Fiber-Optic Strain-Gage Tank Level Measurement System for Cryogenic Propellants

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Note: Portions of the Background Section of this paper were reproduced from reference [1].

Abstract *– Measurement of tank level, particularly for cryogenic propellants, has proven to be a difficult problem. Current methods based on differential pressure, capacitance sensors, temperature sensors, etc.; do not provide sufficiently accurate or robust measurements, especially at run time. These methods are designed to measure tank-level, but when the fluids are in supercritical state, the liquid-gas interface disappears. Furthermore, there is a need for a non-intrusive measurement system; that is, the sensors should not require tank modifications and/or disturb the fluids. This paper describes a simple, but effective method to determine propellant mass by measuring very small deformations of the structure supporting the tank. Results of a laboratory study to validate the method, and experimental data from a deployed system are presented. A comparison with an existing differential pressure sensor shows that the strain gage system provides a much better quality signal across all regimes during an engine test. Experimental results also show that the use of fiber optic strain gages (FOSG) over classic foil strain gages extends the operation time (before the system becomes uncalibrated), and increases accuracy. Finally, a procedure is defined whereby measurements from the FOSG mounted on the tank supporting structure are compensated using measurements of a FOSG mounted on a reference plate and temperature measurements of the structure. Results describing the performance of a deployed system that measures tank level during propulsion tests are included.*

Keywords *– Fiber Optic Strain Gage, Tank Level Sensor*

I. BACKGROUND

Although much has been done to apply fiber optic technology to design a variety of sensors, few are truly commercially available. Classical temperature, pressure, and strain sensors have not been displaced by this new technology to any significant extent. There could be important advantages to using fiber optic (FO) sensors over resistance, piezoelectric, or thermoelectric sensors, but these cannot be realized until FO sensors are demonstrated to be "better" than classical sensors, if only for some applications.

Foil Gages are widely used to measure strain. They are small, and have gained wide acceptability across the scientific and engineering community. However, FG have some shortcomings where FO sensor technology may offer, perhaps, a better alternative.

A change in ambient temperature produces four effects on a foil gage and specimen [2]: (1) the gage factor $S_g = \frac{dR/R}{\varepsilon}$ (or sensitivity) changes, (2) the grid expands or contracts ($\Delta l / l = \alpha \Delta T$), (3) the specimen expands or contracts ($\Delta l / l = \beta \Delta T$), and (4) the gage resistance changes ($\Delta R / R = \gamma \Delta T$). The change in gage factor is usually negligible unless the specimen undergoes very large temperature excursions. The remaining three effects combine as follows to produce a potentially significant change in resistance:

$$\left(\frac{\Delta R}{R} \right)_{\Delta T} = (\beta - \alpha) S_g \Delta T + \gamma \Delta T \qquad (1)$$

where

α is the coefficient of thermal expansion of the gage alloy

β is the coefficient of thermal expansion of the specimen material

γ is the temperature coefficient of resistivity of the gage alloy

These effects produce a thermally induced mechanical strain in the gage that does not occur in the specimen. In contrast, the fiber optic sensing element is simply an empty cavity that strictly follows dimensional changes in the specimen. A combination of specially engineered materials and circuit designs have been developed to deal with the apparent strains in FG, but they have the effect of reducing the operating temperature range and the sensitivity of the strain gage-Wheatstone bridge. The temperature effects exhibited by FG may also be produced by self-heating of the resistance element.

A. White Light Fabry-Perót Fiber Optic Strain Gages (FPFOSG)

These sensors consist of a multimode optical fiber that transports white light, with the sensing element at the tip. The sensing element is defined by a micro capillary tube that holds the end of the fiber close to another small piece of the same fiber, leaving a cavity in between [3-5](Figure 1). The fiber-ends that define the cavity are deposited with mirrors, so that the white light entering the cavity is reflected, and hence frequency-modulated in accordance to this length. When the sensor is bonded to a surface, the length of the cavity in the micro capillary expands or contracts exactly by the same amount of strain experienced by the surface .

$$\left(Strain = \frac{\Delta L_{Cavity}}{L_{Gauge}} \right).$$

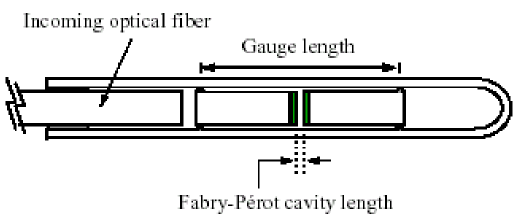

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Figure 1 Fabry-Perot FOSG: Schematic (Courtesy of FISO Technologies, Inc. [6])

The modulated light returning from the sensing element is interpreted using a white light cross-correlator. This device matches the sensor's cavity-length to the thickness of a specific location in the variable-thickness lens [4](Figure 2). The light transmitted through this specific location in the lens contains the highest level of energy as a result of modulation in the sensor cavity. The light is detected by a CCD array, where the pixel receiving the highest amount of energy corresponds to the sensor cavity-length. Each pixel of the array corresponds to a specific cavity length.

Temperature compensated FOSG are also available. These units null-out strain on the measurand due solely to temperature variations. Compensation is accomplished by the use of a metallic fiber with the same thermal coefficient of expansion as that of the material being measured (Figure 3).

White-light Fabry-Perót interferometry fiber-optic strain-gages are robust, exhibiting a design that leaves little room for variation/degradation in performance. Measurement of the cavity length is encoded by light-frequency rather than amplitude, thus significant variations in performance by the light sources do not affect the sensor's performance.

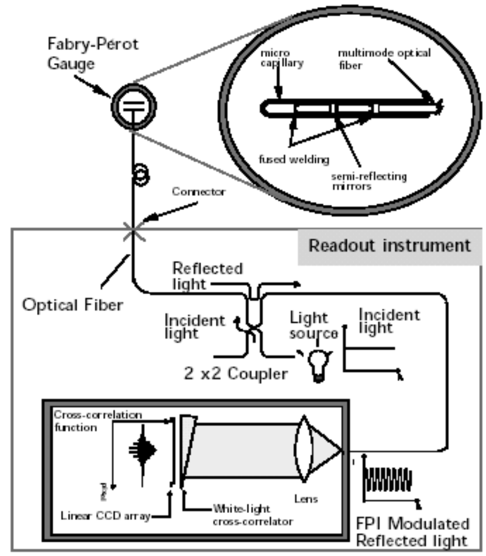

Figure 2. FOSG Signal Conditioning Components (Courtesy of FISO Technologies, Inc. [6])

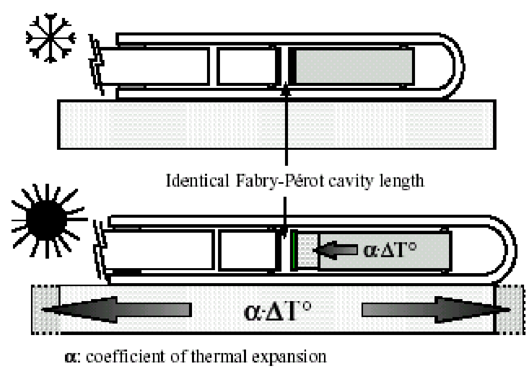

Figure 3 Temperature compensation (Courtesy of FISO Technologies, Inc. [6])

A laboratory study to determine the performance of FOSG is described in [7]. It indicates that FOSG have similar linearity and repeatability as foil gages, but are less accurate. The study is not focused on small deformations as is the case in this paper.

II. DEPLOYMENT AND FIELD MEASUREMENTS

Given that FG have similar experimental resolution than FOSG [1], deployment was first done using FG. To optimize resolution, four gages (a complete bridge) were used in each of four legs (beams) supporting a LOX tank. In each beam, two sensors were mounted on one side (one along the major deformation axis and the other perpendicular to the axis), and the other two on the other side. This was done to eliminate the effect of bending strains. Readings from the FG were taken during a regular test program. Signals from a differential pressure (DP) sensor and the FG sensor system (the sum of signals from the four legs) were compared. Qualitatively, the FG sensor system is superior, but the accuracy of the FG system is affected when exposed to temperature changes and direct sun radiation.

Erratic behavior of the foil strain gages (FSG) was measured when subjected to radiation from the sun and to temperature changes during a cycle of 24 hours. This behavior would limit the use of the technology to short periods of time, during which the radiation level and temperature did not experience changes that significantly affected the measurement. After each short period of operation, the remaining tank fluid mass would need to be assessed by other means to recalibrate the system. In order to overcome this shortcoming, further tests were carried out using fiber-optic strain gages (FOSG), with the expectation that these sensors would not exhibit the same erratic behavior as FG. Tests would also include using a different mounting arrangement of the FSG to minimize or eliminate the erratic behavior.

Results from the FOSG tests indeed show that these sensors exhibit a predictable behavior. Figure 4 shows a plot with measurements taken every 20 seconds for approximately three 24-hour periods. The deformations of the reference plate are clearly a function of temperature, but the deformations of the beam are also affected by constraints from linkages attached to the structure (e.g. pipes). Henceforth, measurements on the tank support structure can be compensated using two other measurements. One from a fiber optic sensor mounted on a reference plate subjected only to environmental thermal effects, and a second from a temperature sensor mounted on the structure.

Given the experimental results with FOSG, a procedure to calculate a compensated measurement (a measurement reflecting the mass contents of the tank) using the FOSG was developed. First one must characterize the structure as it deforms due solely to thermal effects by taking measurements over a 24-hour period when the tank is empty. During this characterization procedure, deformation and temperature measurements are taken from the sensors attached to the structure (strain and temperature) and the sensor attached to the reference plate (strain). With this information a tabulated or graphical tool is developed such that at any given temperature, the reference signal is subtracted from the structural signal, and further modified by a value that depends on the structure's temperature. This value is given by the difference between the beam sensor and the reference sensor(s). Note that the characterization of the structure as it deforms due to temperature variations may also be done by analytical methods that can model the process. In that case, the experimental characterization is not needed.

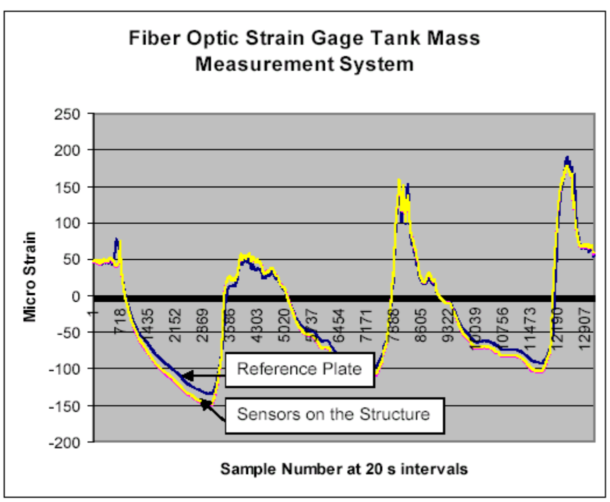

Figure 4 Plot showing the two FOSG mounted on the beam and the gage mounted on the reference plate.

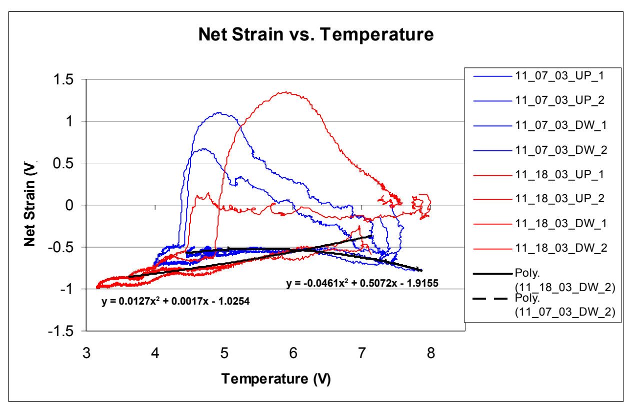

Figure 5 Temperature Characterization of the Support Structure

Figure 5 shows a curve that characterizes the structure as it deforms when subjected to temperature variations only. Because sun radiation and cloud cover are unpredictable, two types of curves were developed. One showing the effects of temperature increase and a second showing the effects of temperature decrease. When the temperature increases, it usually occurs at a faster rate than when it decreases. It also occurs when sunlight and cloud cover impinge on the structure in an unpredictable manner. These curves have a similar shape, but are shifted and have different magnitudes for each data set. However, when the temperature is decreasing, it happens at a slower rate and the curves for all data sets are very similar. These curves correspond to conditions when sunlight does not impinge on the structure, and the deformations become predictable with temperature.

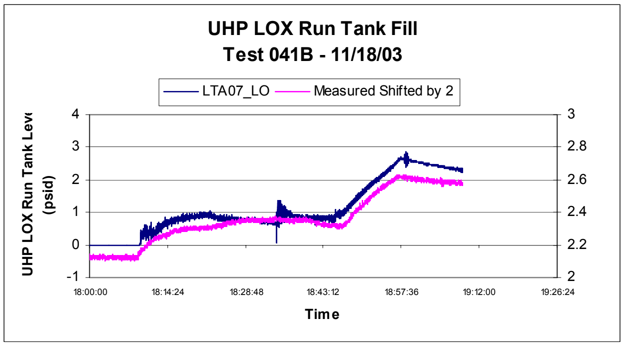

Figure 6 Tank Fill Data

Figure 6 shows test data when a tank is being filled. The total voltage change as the tank goes from empty to full is about 1 Volt per sensor. As the sensor data is added, the voltage change is approximately 2 Volts. This value is comparable to the dynamic range of the differential pressure (DP) sensor currently used to determine the amount of liquid oxygen in the tank (LTA07-LO). However, the quality of the signals of the fiber optic sensors is superior to that of the DP sensor. Two more fiber optic sensors could be added to increase the dynamic range while maintaining the signal to noise ratio equivalent to the DP sensor. The DP sensor also shows unusable data whenever the system is pressurized. As the DP sensor is based on pressure changes inside the tank, it measures artifacts that are not related to change in fluid mass (e.g. boiling of cryogenic fluids, quick unbalances on differential pressure caused by opening and closing of valves, etc.)

III. SUMMARY OF SIGNIFICANT DEVELOPMENTS ASSOCIATED WITH THE USE OF FOSG AND FSG

A. FOSG Performance

When subjected to sun radiation, fiber optic sensors, indeed do not exhibit unpredictable erratic behavior, as was the case with the foil gages. The FOSG exhibit a very predictable behavior associated with temperature variations throughout a 24-hour operating cycle. This provides a foundation to develop a compensation method to determine a value that represents accurately the mass contents of the tank.

B. Strain and Temperature Measurements

Experimental measurements show that the fiber gages on the structure experience a slightly different thermal strain than the gage on the reference plate. This is because the thermal deformation of the structure is restricted by other attachments. The structure is not free to dilate or contract, as is the reference plate. The difference in the strain measurements is temperature dependent, and again, it is predictable.

C. Method of Compensation

In order to determine a value that reflects accurately the mass contents of the tank, the following compensation procedure is needed. First, a thermal deformation characterization of the structure must be performed. In this case, it was done experimentally by measuring deformation in the structure and reference plate, as well as the temperature of the structure, throughout various 24-hour cycles (See Figure 5). The characterization measurements provided the data to develop a chart or look-up table whereby for each temperature value of the structure, there is a corresponding value representing the gap between the structural and the reference strain measurements. In Figure 5, the gap is given by the difference between the "Sensors on the Structure" values and the "Reference Plate" value. This gap and the value of the reference plate are used to compensate the structural strain measurement and obtain a value that accurately estimates the tank mass contents at a given temperature of the structure.

IV. CONCLUSION AND RECOMMENDATIONS

A new technology has been developed to measure the mass contents of a tank. The measurement system is based on use of fiber optic strain gages and includes three components. A set of gages mounted on the structure supporting the tank (more sensors will increase the resolution), a gage mounted on a reference plate to compensate for deformations caused by temperature variations, and a look-up table or plot developed (experimentally or analytically) to characterize the structure's deformation when subjected to thermal effects only.

Improvements to this technology can accrue from design of fiber optic sensors with a longer measurement distance. This would increase the resolution. Fiber optic extensometers are just becoming available, and these may address this issue. Perhaps one could also design the tank supporting structure such that it deforms maximally without compromising its integrity. Again, this would increase the resolution of the measurement system.

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