Material Removal Rate Fiber Optic Corrosion Sensor

Angela Trego, Eric Haugse and Eric Udd
Structures & Technology, Phantom Works
Information, Space and Defense Group
P.O Box 3999 MS 82-97
Seattle, WA 98124 - 2499

Introduction

Fiber Bragg grating sensors generally consist of a single grating written in a low-birefringent optical fiber. The wavelength shift of the peak in the reflected spectrum from these sensors can be used to measure a single component of strain or a change in temperature [Lawrence, 1997]. Fibers are also available with a significant enough birefringence to maintain the polarization state along great lengths and through many turns. This "polarization maintaining" fiber is commercially available through several companies and in several configurations (including different cladding material and wavelength shift). The grating usually extends approximately 3mm - 5mm in length. Udd gives a detailed explanation of fiber optics, Bragg gratings and birefringence [Udd, 1991]. As light from an LED is passed through the fiber, only the wavelength consistent with the grating period will be reflected back towards the source. All other wavelengths will pass through. The reflected spectrum will shift as the fiber is strained along its axis at the grating location. Strain or temperature changes at any other location have negligible effect on the wavelength encoded data output. When the Fiber Bragg grating single-axis sensor (termed fiber hereafter) is strained transversely the wavelength will separate into two distinct peaks according to a mathematical relationship defined by Lawrence and Nelson [Lawrence, Nelson et. al. 96].

Using these Fiber Bragg grating fibers a corrosion sensor which measures the rate of material was developed. The principle behind this newly developed corrosion sensor is to pre-stress the fiber with a known load. The load is applied by inducing a uniform hoop stress through pressure fitted cylinders around the fiber. This induced stress creates a broadening of the reflected spectrum until the bifurcation of the reflected intensity peaks is distinguishable. As the material from the outer cylinder corrodes away the applied stress will be relieved. Finally, when no load is achieved, the reflected spectrum will have a single peak centered around the nominal Bragg grating wavelength. If a polarizing-maintaining 3-axis grating is used then the sensor would be even more sensitive, having two distinct peaks in each wavelength regime which shift.

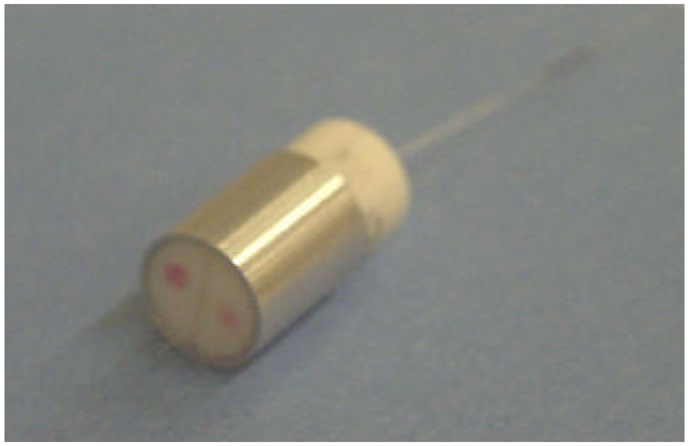

Figure 1. A partially completed assembly of the corrosion sensor developed by the authors (Actual prototype size: 0.4" L x .25" Dia).

Sensor Design

Several factors are necessary when designing the sensor. First, the materials must be properly chosen. The outer cylinder's material should be congruent with the medium it is to detect for corrosion. For example, if the sensor were attached to a commercial jet it would most likely be made from 2024-T3 Aluminium. This is necessary to

1. Properly determine the corrosion rate on the desired material and
2. Not induce accelerated corrosion growth rates because dissimilar materials create galvanic coupling.

The inserts, which are required to produce a more uniform loading field on the fiber, are made of an inert, low CTE material such as macor to allow easy assembly of the prototype. Again, proper material selection is essential. If dissimilar materials are chosen then a galvanic coupling would occur, causing falsely high corrosion rates between the insert and the outer cylinder. If the insert and outer cylinder materials chosen have varying CTE's then the induced strains on the fiber would appear to exhibit a change in corrosion rates as well.

The load on the fiber is predetermined according to the interference fit relationship:

$$d = d_o - d_i = \frac{bp}{E_o}\left(\frac{c^2+b^2}{c^2-b^2}+n_o\right)+\frac{bp}{E_i}\left(\frac{b^2+a^2}{b^2-a^2}+n_i\right)$$

where:

- δ = Total radial interference fit
- δ_x = Respective radial interference fits
- p = Applied Pressure
- E_x = Respective elastic modulus of the material
- ν_x = Respective Poisson's ratio
- a = Inner radius of the insert
- b = Outer radius of the insert
- c = Outer radius of the outer cylinder or sheath.

Applying this formula one can create the proper interference fit between the inserts and the outer cylinder to achieve the desired loads. It is important to create a large enough load to separate the peaks far enough to detect more easily when corrosion occurs.

Assembly

A prototype was designed and fabricated at the Boeing environmental test laboratory for a proof of concept test. Once the macor and aluminium inserts were designed the fabrication procedure followed as illustrated in Figure 2. (NOTE: This is not a production assembly. There are developed practices in industry to assemble press fits):

- A fiber optic cable with a Fiber Bragg grating sensor is threaded through the plastic jig.
- The macor inserts are positioned in the plastic jig. The sensor part of the fiber optic needs to be encompassed or surrounded by the inserts. It is also important not to kink the fiber optic under the plastic jig
- The outer aluminium sleeve is heated until its inner diameter has expanded greater than the fiber plus inserts assembly.
- The aluminium sleeve is slid over the assembly.
- As the aluminium sleeve cools it contracts, creating a designed transverse strain on the optical fiber.

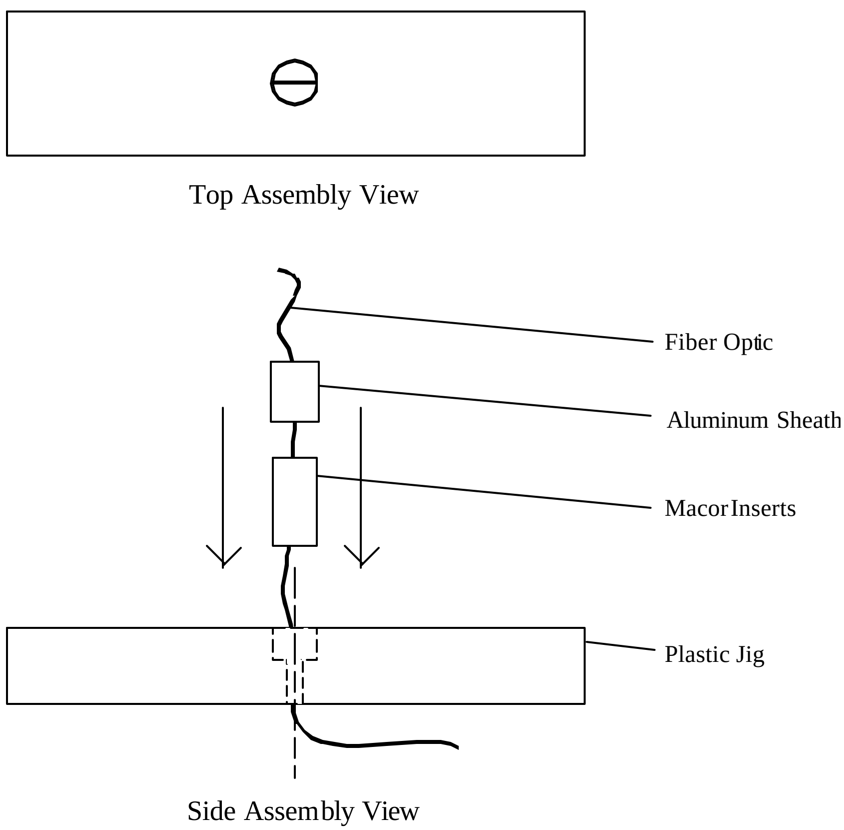

Figure 2. Fabrication Procedure.

Output

Once the corrosion sensor is assembled the aluminium sleeve is allowed to cool over the macor inserts. Upon cooling, the sensor in the fiber is loaded. The typical output may appear as in Figure 3.

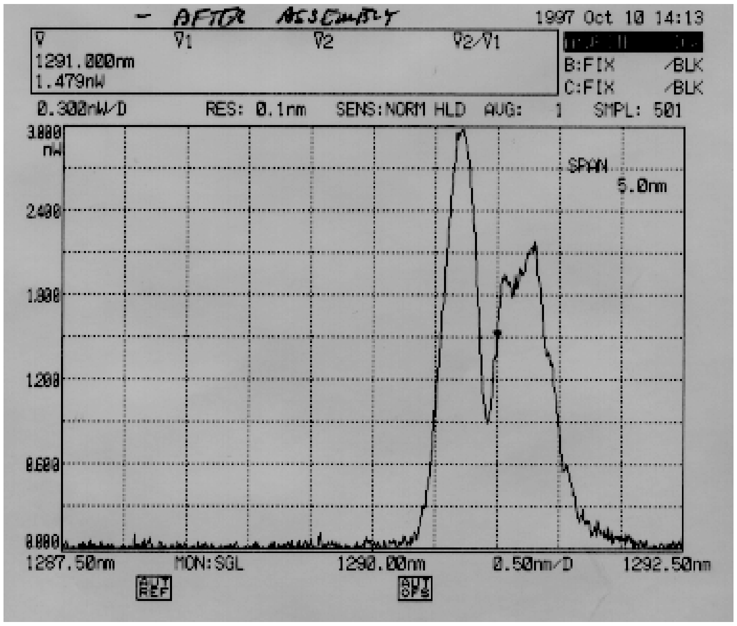

Figure 3. Corrosion sensor readout in initially loaded position.

A mathematical relationship between the resulting applied load of the fiber and the photoelastic characteristics of the fiber has been developed [Lawrence, Nelson 96]. As material corrodes away the load will be released according to a calibrated amount of material loss, predictably changing the photoelastic characteristics. A correlation may be made between the amount of material loss and the distance between peak separation. From this, maintenance workers may determine if inaccessible regions require repair and at which location. Once the load has been completely released (for example, the aluminium band has corroded away) the single-axis sensor will have a typical output as shown in Figure 4. Figure 4 is also how the fiber will look initially before loading, with the reflected spectrum centered around the nominal Bragg grating with a single peak.

Testing

Currently, testing is being performed at Boeing, ISDS in Seattle, Washington to determine the corrosion sensor's sensitivity in determining corrosion. A prototype (as shown in Figure 1) was assembled and placed in a salt spray chamber. Results are forthcoming.

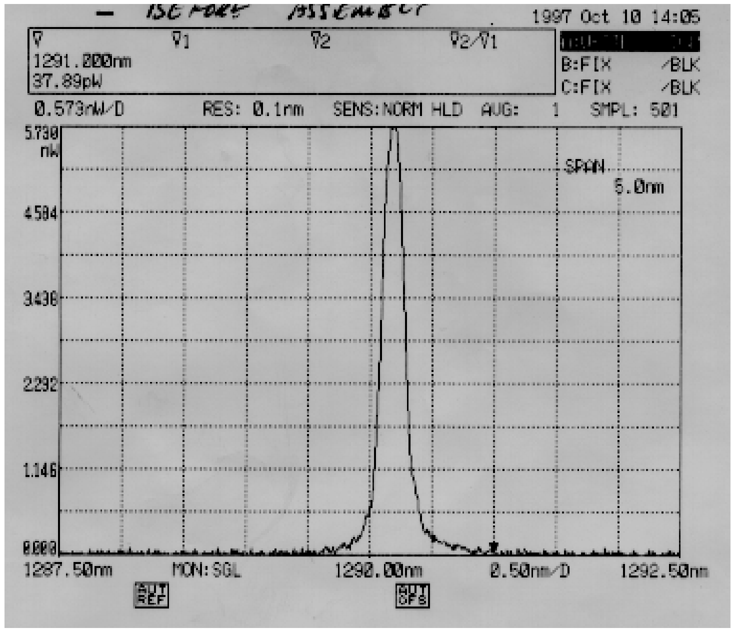

Figure 4. Corrosion sensor readout in unloaded position.

Advantages

There are several advantages to using the design of this fiber optic corrosion sensor. The method of fiber optics is extremely accurate and not susceptible to limiting environmental effects. Sensitivity of these sensors could be increased by using a dual peak Bragg grating which has two wavelengths of reflected light rather than a single wavelength of reflected light. The pre-loading on the sensors, a hoop stress, tends to be an extremely stable configuration. Furthermore, these gratings may be placed along several points of the fiber optic allowing for several sensing points with only a single input / output point reducing the amount of equipment necessary. Fiber optics are extremely light weight which could reduce cabling weight by integrating several sensors into a single fiber optic cable within the structure's framework. Corrosion in hidden or inaccessible locations is particularly costly. In general, by the time it is detected without disassembly, corrosion damage is so extensive that massive repairs are required. Disassembly is time consuming, costly, and often results in additional damage to the aircraft. The cost saving realized in detecting hidden corrosion without disassembling the structure would be significant.

Bibliography

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