A FIBER OPTIC RF RESONANT CAVITY SENSOR FOR STRAIN SENSING - FORRCS

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INTRODUCTION

A fiber optic vibration and strain sensor described by Rogowski et al [1] implemented a radio frequency (rf) phase locked loop in an optical strain gauge bonded to or embedded in a composite structure. A laser is modulated at radio frequency by a voltage controlled oscillator. The phase delay through the optical fiber transmission line is compared to the source oscillator, and the resulting error signal shifts the oscillator, locking the phase. Strain in the specimen (a composite panel) produces a change in optical phase length in the fiber. Tracking the frequency change gives a measure of the integrated strain transduced into the fiber from the strained panel. Strain level sensitivity on the order of 0.1 microstrains has been reported [1]. However, considerable confusion surrounds the performance of the reported sensor, since noise presumed to arise from cladding/core mode interference and splice reflections makes significant filtering necessary, reducing the bandwidth of the sensor, e.g., increasing the response time to detect strains [2]. This limits vibration control applications.

The sensitivity of this system, and its stability, are dependent on the rf signal phase slope (or Q, quality factor) of the delay around the circuit. If the amplitude of the propagating rf signal, frequency f, behaves periodically, i.e., as $\exp[i\phi] = \exp[ik \bullet L]$, where L is the propagation length from laser to detector through the fiber and k is $2\pi/\lambda = 2\pi f/c'$, and λ is the rf wave length propagating in the fiber at the speed of light c', then the phase slope is $\partial\phi/\partial\omega = L/c'$, where $\omega = 2\pi f$. Clearly, increased sensitivity is proportional to the fiber length L, but it may not be expeditious to embed the additional fiber in the structure. While excess lengths of fiber external to the component can be accommodated, the specimen length will be somewhat smaller, and specimen strain will account for distortion of only a portion of the total fiber. Excess fiber may also be subject to spurious disturbances which will produce false indications of strain not arising within the structure and add to the signal noise. Thus, increasing fiber "lead" length to increase phase slope does not increase the actual amount of fiber susceptible to strain, nor does it increase sensitivity, but it does increase the susceptibility to spurious random and systematic error.

Increasing the effective optical path length (within the structure) without increasing the actual length of embedded fiber can improve the magnitude of the phase delay slope without exposing the fiber to additional spurious disturbances. This can be accomplished by making the structurally embedded fiber function as a Fabry-Perot cavity (at radio frequency wavelengths) which effectively folds the optical path over on itself many times. The fiber loop forms a cavity that is an integral number of wavelengths long at multiples of some fundamental radio frequency.

We report on tests of a sensor based on this configuration, in which the optical fiber connecting the laser and detector is coupled to an optical fiber loop embedded in a composite structure through a 2x2 fiber coupler. The sensor has been modeled and the resulting analysis shows that it obeys the characteristics of a Fabry-Perot cavity.

Samples of composite panels were fabricated and experiments were performed in which these were strained to failure parallel to the optical fiber axis. In some instances the specimens were strained to failure at 0.75%.

The experimental procedure incorporates the use of rf electrical network analysis measurement techniques interfaced to the optical circuits. The resulting strain data is presented and analyzed to extract the effective gauge factor for the fiber.

FORRCS - FIBER OPTIC RF RESONANT CAVITY SENSOR

The sensor described extends the sensor design demonstrated by Rogowski with an enhancement that incorporates the increased sensitivity of a Fabry-Perot interferometric cavity. The sensor system is illustrated in Figure 1. A network analyzer operating in

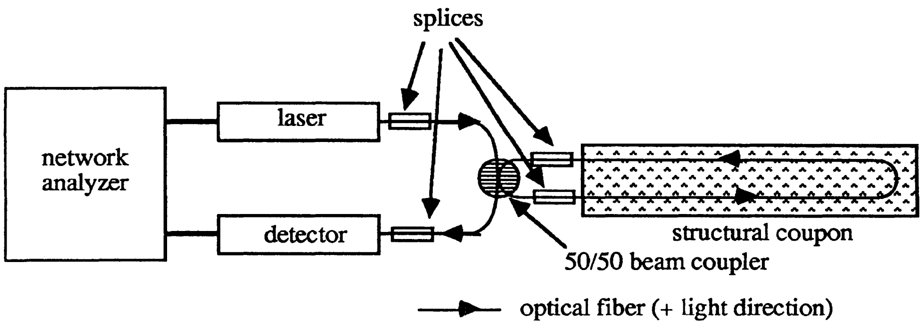

Figure 1. Fiber Optic Resonant Coupled Cavity Sensor - FORCCS.

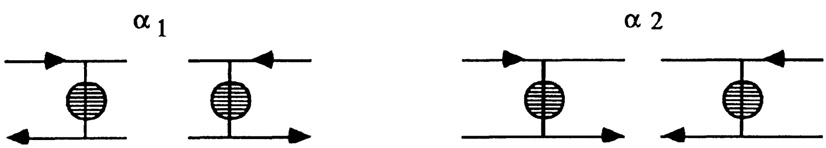

Figure 2. Nomenclature for definition of α_1, α_2.

transmission mode (S_{12}) was used to provide the modulation signal driving the diode laser. The laser was directly coupled to the optical fiber (a standard 50 micron core/ 125 micron clad silica communications fiber) and terminated at a detector after passing through a 50/50 (i.e., 3 dB) fiber coupler. Splices are indicated to show how discrete components - laser/detector pigtails, coupler and specimen - are all connected. The quality of these splice connections plays a role in the performance of the sensor.

In this concept a fraction α_2 of the rf modulation signal amplitude (A) is coupled into the structure as well as α_1 directly to the detector. Coupler reciprocity dictates that α_2 also describes the fraction of light in the structure that exits through the coupler toward the detector and α_1 describes the fraction of light energy in the coupon that recirculates after passing through the coupler. This is illustrated schematically in Figure 2. In the absence of internal losses $\alpha_1 + \alpha_2 = 1$.

Each time the light circulates through the coupler, a fraction is returned to the structure for recirculation. The signal amplitude I received at the detector is the sum of all the terms obtained by adding the infinite series

$$I = A\{\alpha_1 + \alpha_2 e^{ikL}\alpha_1 e^{ikL}\alpha_2 + \alpha_2 e^{ikL}\alpha_1 e^{ikL}\alpha_1 e^{ikL}\alpha_2 + \cdots\} \qquad (1)$$

$$I = A\left\{\alpha_1 + \frac{\alpha_2^2 e^{ikL}}{[1 - \alpha_1 e^{ikL}]}\right\} \qquad (2)$$

where L is the length of the loop. The term kL describes the path phase delay for each circuit around the loop. Electrical phase delays between the network analyzer and the laser and detector (of length L_x) are ignored.

The detected rf power is given by

$$|I|^2 = A^2\{\alpha_1^2+[\alpha_2^2-\alpha_1^2]^2+2\alpha_1[\alpha_2^2-\alpha_1^2]\cos(kL)\}/(1+\alpha_1^2-2\alpha_1\cos(kL)) \qquad (3)$$

From an examination of (3) we can see that a minimum nonzero signal is obtained for any combination of α_1 and α_2 even at antiresonance, i.e., when kL is an odd multiple of 2π.

The function

$$F = 1/(1 + \alpha^2 - 2\cdot\alpha\cdot\cos(kL)) \qquad (4)$$

is the Airy formula, and is well known for describing the transmission characteristics of a cavity formed by two parallel partially reflecting surfaces, e.g., the Fabry Perot interferometer [3].

It is clear from examining (3) or (4) that the maxima in transmission occur when

$$kL = 2\pi f_r(j)\, L/c' = 2\pi j, \quad j = 0,1,2,.... \qquad (5)$$

Thus for a given fiber loop length L, successive peaks are expected as the frequency is swept.

Equation (3) represents a description of a modified Fabry-Perot cavity. It differs in detail from a classical optical Fabry-Perot Airy function as a consequence of the "geometry" of the optical circuits and the properties of the optical couplers.

We have built the system shown in Figure 2. A typical rf spectral response is shown in Figure 3. It obeys the form of equation (4) quite faithfully. An accurate determination of L/c' can be obtained from the data. An independent measurement of L can be made, and c' can be obtained from the fiber supplier's data sheet.

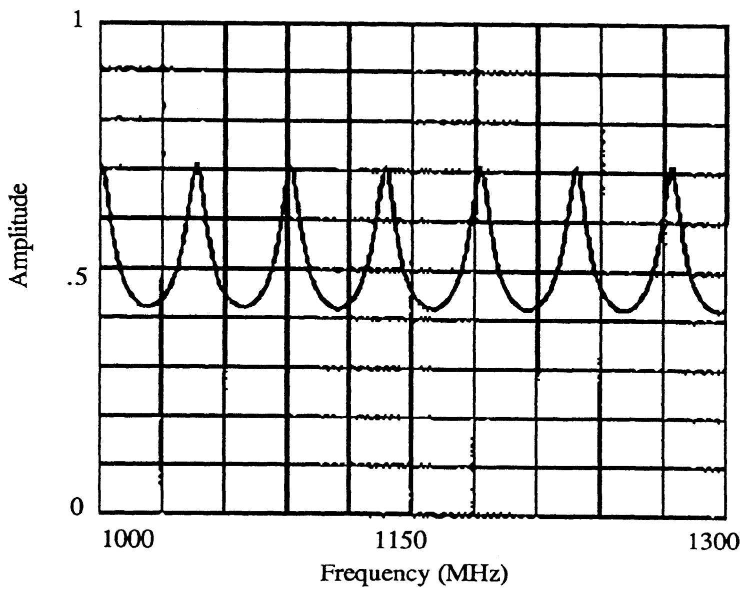

Figure 3. Associated rf amplitude spectrum.

IMPLEMENTATION AS A SENSOR

If the fiber is allowed to exhibit strain, as would occur when embedded in a flexible structure, then, the frequency location of the resonance peaks will modulate with the strain as the absolute path length L changes (Eqns. (3) and (5)). Higher order resonances will shift more than the first resonance, like a spring fixed at one end and free at the other.

We have taken advantage of the resonant cavity properties of the loop by measuring the phase shift at a fixed frequency corresponding to a resonance peak in an unstrained specimen state. This is the frequency at which the unstrained loop phase delay is zero or a multiple of 2π.

EXPERIMENT

The first specimen consisted of 10 layers of .005 in. thick unidirectional Gr/Ep prepreg with the optical fiber embedded between the 5th and 6th layers, within a sandwiched layer of syntactic core foam (hollow microspheres embedded in epoxy), as shown in Figure 4. The intended purpose of the foam was to provide a medium in which the fiber could be embedded without being deformed or sheared by compression against the graphite fibers. The total length shown corresponds to the sample portion between the two grippers. The optical fiber was polyimide coated 50/125 micron multimode communications grade fiber (Superguide G from Fiberguide Industries, Inc.). "Leader" fiber was spliced to each end of the embedded fiber with Norland SpliceMates, which were used throughout. The ring structure and coupling to the external laser/detector circuit were made through an Aster 50/50 multimode splitter. A load cell measured applied load (in kg) and strain was measured with a two-inch reference extensometer attached to the sample. Load frame data was plotted on a two-pen strip chart recorder. The network analyzer measured phase delay at a single frequency corresponding to a resonance peak in the unstrained sample.

The stress/strain values are obtained from applied loads, the geometry of the specimens and extension data. In the case of the foam core sandwich specimen, average modulus and weighted stress values were used to obtain quickly coarse estimates of the gauge factor of the FORCCS. The coupon failed at 1900 lbs (862 kg), corresponding to an effective load stress of 21.6 kpsi and a failure strain at .0074 in/in. The composite Young's modulus for the sandwich structure was 2,920 kpsi. This may not be a fair estimate, since the load path may not be uniformly distributed between the Gr/Ep and the foam region. The FORCCS system for this experiment demonstrated a gauge factor of 83 microdegrees/lb (38 microdegrees/kg). This translated to an effective strain gauge factor (based on load and extension at failure) of approximately 20 degrees/in/in. The gauge length of the fiber was 7.5 in., the distance between the ends of the two grips.

Several laminated composite coupons without syntactic foam were fabricated. One sample was tested. The thickness of these coupons was in the range of 0.050 in. Figure 5 is the phase versus load dependence for this sample. The zero load intercept of 6.9 millideg is an arbitrary reference. The FORCCS is reasonably linear, with a standard deviation error of approximately +/- 1 millidegree. The gauge factor is 311.6 microdegrees/kg. This is almost ten times more sensitive than the result obtained for the syntactic foam sandwich coupon (38 microdegrees/kg). We estimate that the strain gauge factor is approximately 164 degrees/in/in for this sample, with a gauge length of 7.5 in. It should not be concluded that the the foam core is exclusively responsible for the change in sensitivity, although some ductility in the foam may occur. The steepness of the phase slope (i.e., phase vs frequency) is intimately dependent on the absence of losses in the optical loop circuit. In particular, splice losses and coupler inefficiencies will act to lower the resonance Q factor of the cavity, resulting in flatter phase slopes.

CONCLUSIONS

A fiber optic resonant coupled cavity sensor - FORCCS - was developed and applied to test the tension strain gauge capability of optical fibers embedded in two configurations of laminated Gr/Ep composites. One type contained the fiber in a sandwich layer of syntactic foam. The purpose of this was to protect the fiber from any shape distortion that might arise from the weave characteristics of the graphite fabric. No apparent difference in the integrity of the fiber occurs and the fabrication process was considerably more complicated. Strain gauge factors of as high as 164 degrees/in/in have been obtained from load frame testing. Measurements were made using an optical network analyzer. Our conclusion is that the FORCCS is a viable new type of sensor that has promising characteristics for application to structural load monitoring and can survive to the point of failure of the

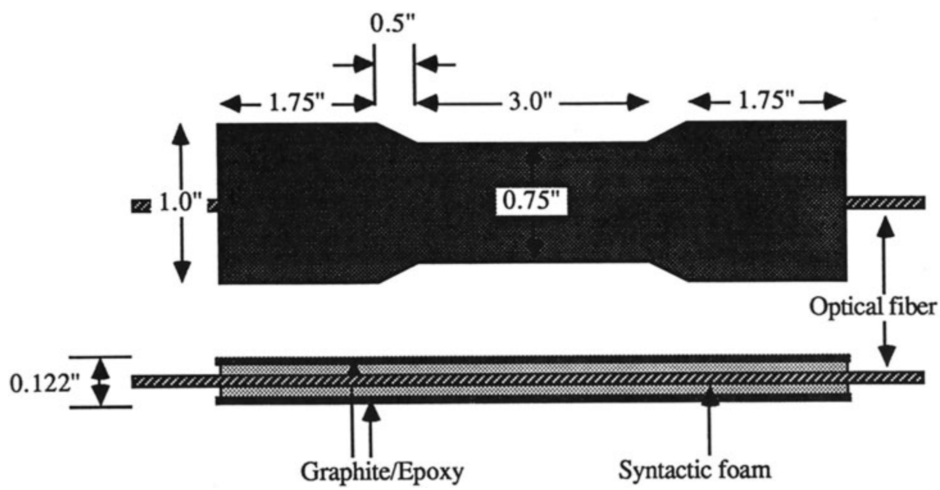

Figure 4. Test sample containing embedded optical fiber.

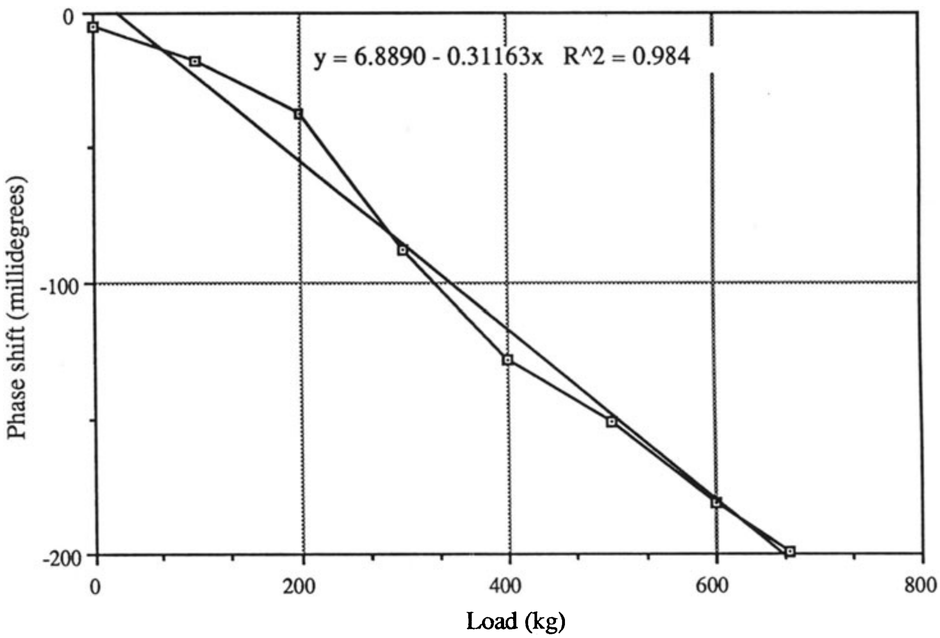

Figure 5. Typical phase dependence on load response of FORCCS.

structural host. Compression, shear and torsional sensing have yet to be evaluated. The sensor system internal noise, another area of investigation, currently limits application to conditions where minimum detectable strain is greater than 1 microstrain up to approximately 1000 microstrains.

ACKNOWLEDGEMENTS

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