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ABSTRACT

Optical fiber sensors promise to play a large role in the development of *smart structures* which have the ability to continuously monitor themselves for internal and external structural deformation, and even actively change shape. This investigation studies one such sensor based on a fiber optic Fabry-Perot interferometer, which detects the displacement between two points of a material. Sensor theory and construction are discussed, and the tools used to analyze sensor output are developed. The interferometer is then tested by attaching it to a large cantilever beam which is deflected to produce strain. This experimental data is then used to determine Fabry-Perot cavity performance, to predict sensor accuracy and resolution, and to develop a method for relating material strain to sensor output.

INTRODUCTION

The search for strong, lighter-weight materials for use in aerospace and advanced automotive applications has led to development of replacements for traditional sheet metal and aluminum. Much success has been obtained in the area of composites, which are materials formed by bonding two dissimilar components to create a more desirable final product. One common composite type is constructed from brittle fibers held together by a more pliable binding material [1].

Due to the complexity of manufacture and application of composite materials, it would be useful to monitor integrity of the material to detect excessive internal stresses or delaminations. The class of composites which are able to continuously monitor and even manipulate structural characteristics are collectively known as smart materials, or *smart structures*. Methods for constructing these materials involve embedding sensors and actuators within the composite itself. These smart structures could improve reliability and reduce waste during manufacture, and could continuously adjust themselves in an aerospace application, for instance.

Advancements in the area of fiber optic sensors brought smart structures one step closer to reality. Fiber optic sensors are ideal for embedding in composites because they are very small, lightweight, immune to electromagnetic interference, environmentally rugged, and can be incorporated in composite materials [2]. These sensors operate by detecting the difference between a reference light signal and a return signal which has been perturbed by the sensor measurand. In many cases this measurand is displacement between two points on the structure, but cracks or stresses in the material can also be detected by optical micro-bend or pressure sensors.

A simple way to measure material strain is by detecting a displacement between two points on the structure. This investigation utilized an intrinsic fiber optic Fabry-Perot sensor to determine displacement between two points of a material, corresponding to strain. The test material was a large aluminum beam cantilevered at both ends. Lateral deflection of the center of the beam caused maximum strain in the center and at both (fixed) ends, thus the fiber optic sensor was attached at center of the beam. Results allowed calculation of sensor parameters, and insight into the relationship between sensor output and strain in the beam.

BACKGROUND

Simple fiber optic Fabry-Perot sensors are a fiber implementation of a geometrical Fabry-Perot interferometer. Two fibers form an air gap which acts as a low finesse Fabry-Perot cavity, whereas interference of light reflected from the glass/air and air/glass interfaces produces an output intensity related to the length of the air gap. Construction of a reflection Fabry-Perot sensor typically utilizes a single-mode fiber as the input-output fiber, and a multi-mode fiber which acts as a reflector, as shown in Figure 1.

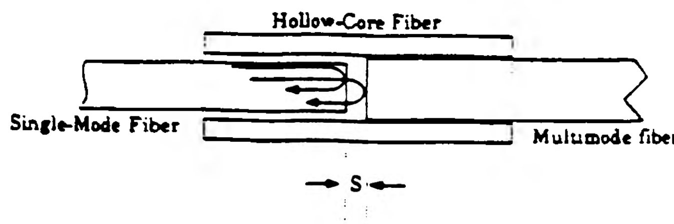

Figure 1. Construction of Extrinsic Fabry-Perot Sensor [3].

The far end of the multi-mode fiber is shattered to prevent back-reflections. Fresnel reflections from the first (glass/air) interface act as the reference signal which interferes with the sensing signal from the second (air/glass) interface in the single-mode fiber. When the two fibers are allowed to move in the hollow-core fiber, changes in air gap length cause the intensity of the return signal to change due to changes in phase difference between the interfering reflected signals.

Interference of the reflected signals can be quantified using a plane-wave approximation so that observed intensity at the detector can be shown[3] to be

$$I_{det} = |U_1 + U_2| = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_1 - \phi_2) \tag{1}$$

where $U_i(x,z,t)$ is the complex amplitude of the approximate plane wave for i = 1, 2 for the reference and sensing reflections, respectively, given by

$$U_i(x,z,t) = A_i \exp(j\phi_i), \qquad i = 1,2 \tag{2}$$

Thus detected intensity can be represented as the sum of the reference and sensing reflections.
Equation (1) can be simplified[3] to become

$$I_{det} = A^2\left(1+\frac{2ta}{a+2s\tan\left[\sin^{-1}(NA)\right]}\cos\left(\frac{4\pi s}{\lambda}\right)+\left\{\frac{ta}{a+2s\tan\left[\sin^{-1}(NA)\right]}\right\}^2\right) \quad (3)$$

where it is assumed that $\phi_1 = 0$ and $\phi_2 = 2s(2\pi/\lambda)$, and λ is the vacuum wavelength. In Equation (3), a is the fiber core radius, t is the transmission coefficient of the air/glass interfaces, s is the air gap length, and NA is the numerical aperture of the single-mode fiber. Using this expression, a plot of normalized intensity versus gap separation is shown in Figure 2.

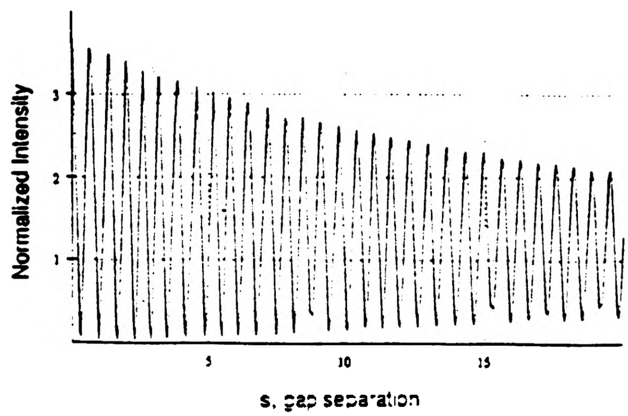

Figure 2. Variation of Output Intensity with Increasing Gap Separation [1]

These expressions can be used if the material properties of the sensor are known with relative certainty. For the purposes of this investigation, using single-mode fiber, the air gap may be further approximated by two parallel glass plates separated by air, and the plane wave assumed to be normally incident on the interface. Cavity parameters can then be determined without knowing material properties. The parameter F is defined in terms of the incident and reflected intensities by[4]

$$\frac{I_r}{I_i} = \frac{F}{1+F} \quad (4)$$

for normal incidence. Cavity *finesse* $\mathcal{F}$ relates the separation of transmitted intensity maxima and their half-intensity width, the points on either side of the maxima where intensity has fallen to half of its maximum value. Higher finesse indicates sharper resolution of reflected intensity minima (transmitted intensity maxima). Finesse is related to F by the expression[4]

$$\mathcal{F} = \frac{\pi\sqrt{F}}{2} \tag{5}$$

Another indicator of cavity performance is *reflectance* R which is related to F by the formula[4]

$$F = \frac{4R}{(1-R)^2} \tag{6}$$

As R approaches unity, F becomes larger, indicating "better" performance from the Fabry-Perot cavity due to increased resolution between maximum and minimum intensity values of the reflected signal.

An extrinsic Fabry-Perot interferometer constructed from optical fiber components retains high sensitivity but possesses the additional advantages of very small size, light weight and ruggedness. The strain sensor assembled for this lab required a fiber Fabry-Perot cavity, a laser diode source (λ_o = 1300nm), a photo-detector, a directional 3dB coupler, and support electronics to power the laser diode and display the received intensity signal. By connecting each side of the cavity to points opposite the center of the experimental cantilever beam it was possible to measure strain between two points on the beam.

EXPERIMENTAL PROCEDURE AND RESULTS

Both the laser diode and the photo detector used FC type connectors for attachment to a fiber optic system. Terminating the Fabry-Perot cavity pigtail, directional coupler fiber ends, and connecting fibers with compatible FC connectors was the first step in constructing the sensor. To accomplish this task, a 3M Field Connector Kit was used, which contained necessary tools to epoxy and crimp the connectors, strip and polish the fiber ends, and verify proper termination. FC connectors ensured proper core alignment with repeated connections and disconnections of single-mode fibers. Unjacketed 5μm single mode communications-grade fiber was used in this investigation for economy in a laboratory environment. Micro-bend insensitive fiber might be necessary when the sensor is incorporated in composite materials, but this difference in connecting fiber would not alter the results of this experiment.

As a test material to correlate beam deflection to sensor output, a 2024 T3 aluminum alloy beam approximately 30cm long was secured at each end to prevent translation or rotation. A micrometer plunger was fixed to displace the center of the beam to induce strain, and the fiber Fabry-Perot sensor was attached across the mid-point of the beam. This experimental configuration is shown schematically below in Figure 3.

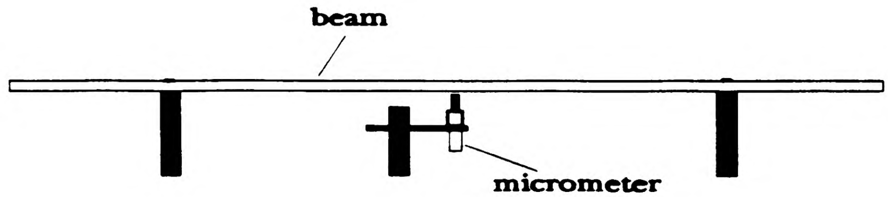

Figure 3. Experimental Cantilever Beam

To verify optimum placement of the strain sensor, MSC/NASTRAN was used to perform a theoretical static analysis of the beam. The nodal analysis provided by NASTRAN verified that when the beam was displaced at the center, strain was greatest at the center and at the cantilevered ends. A plot of strain energy versus distance from the end of the beam is shown in Figure 4.

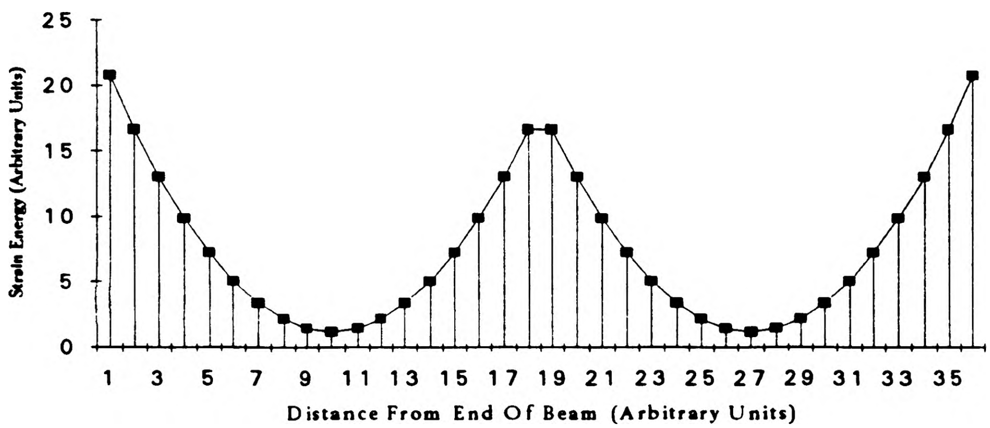

Figure 4. Strain Energy in Beam for Center Displacement

A simple system was constructed to utilize the reflection Fabry-Perot sensor. A laser diode powered by a Tektronix PS5004 current source was attached to one arm of a 3dB directional coupler, which was then attached to the sensor cavity. The return arm of the coupler was connected to a photo detector which converted reflected intensity to voltages which could be displayed on an oscilloscope. The fourth coupler arm was broken to reduce noise from back reflections. A block diagram of the assembled sensor is given in Figure 5.

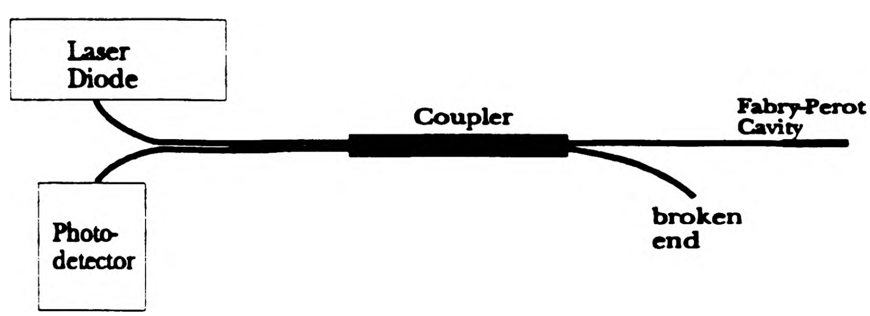

Figure 5. Extrinsic Fabry-Perot Sensor Construction

Once the test beam and interferrometric sensor were assembled, testing could begin to correlate the sensor output to beam deflection, thus to strain in the beam. As the micrometer plunger was used to increase beam deflection, strain on the beam caused the sensor air gap length to increase, changing the relative phase between the reference reflection and sensing reflection. As predicted by Equation (3), the reflected intensity alternated between maxima and minima as the reflected signals alternately interfered constructively and destructively. The beam deflection resulting in several maxima and minima was recorded, and is graphed in Figure 6.

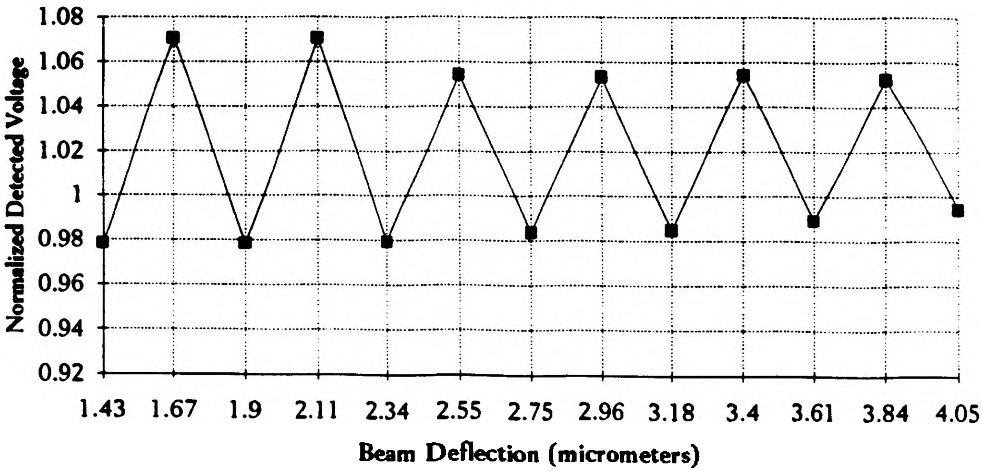

Figure 6. Experimental Intensity Output with Beam Deflection.

The fringe contrast dropped as displacement increased, which is predicted by Equation (3) since the relative intensity of the sensing reflection dropped with respect to the reference reflection. As a performance indicator, the highest maximum corresponded to a photo detector voltage of 98.5mV, compared to a voltage input to the Fabry-Perot cavity of 4.88V.

This experimental data was then used to calculate the finesse and reflectance of the cavity, and to predict the gap length difference corresponding to the difference in beam deflection. Theoretical values can be compared to the calculations, and predictions can be made about the correlation between gap length difference and beam deflection.

ANALYSIS

Experimental results above demonstrate the usefulness of the Fabry-Perot interferometer as a strain and microdisplacement sensor. Construction was simple to ensure small size and ruggedness: the Fabry-Perot cavity is constructed by leaving an air gap between a single-mode fiber and a multi-mode fiber. The finesse of this cavity can be calculated using Equations (4) and (5) and the experimental values listed above.

$$\left|\frac{E_r^2}{E_{in}^2}\right|_{max} = 0.0202 = \frac{F}{1+F} \tag{7}$$

$$F = 0.0206$$

Then finesse is

$$\mathcal{F} = \frac{\pi\sqrt{F}}{2} = 0.2255 \tag{8}$$

and reflectance, by Equation (6) is calculated to be

$$R = 0.0356$$

While this finesse and reflectance is low compared to values which can be obtained by using mirrored reflecting surfaces, the simplicity of the design obviously is an economic advantage when using this sensor. It has been shown[3] that this type of cavity provides adequate resolution up to at least 200 µm displacements, and is especially useful for detecting very small displacements on the order of a single micrometer.

Intensity maxima and minima also reveal information about gap displacement as it relates to beam deflection (material strain). Using the parallel plate approximation with normal incidence, as described in the BACKGROUND section, the order of interference m for maxima and minima of the reflected signal is given by[4]

$$m = \frac{2n_a s}{\lambda_o} \tag{9}$$

where n_a is the refractive index of the air gap (≈ 1), s is the air gap length, and λ_o is the vacuum wavelength (1300 nm). Intensity maxima for the reflected case correspond to half-integral values of m (1/2, 3/2, 5/2, . . .) while minima correspond to integral m values (1, 2, 3, . . .).

Experimental observation of the number of fringes produced for a given beam deflection can then be used to calculate the change in air gap length, thus the strain on the beam. From the results shown in Figure 6, a beam deflection of (4.05 - 1.67) = 2.38 µm resulted in 6.5 observed fringes. Using Equation 9, the resulting change in air gap length is **Δs = 4.2 µm**.

To verify this result, Equation 3 was plotted using some typical values for a single-mode step index fiber and s = 4.2 µm, shown below in Figure 7.

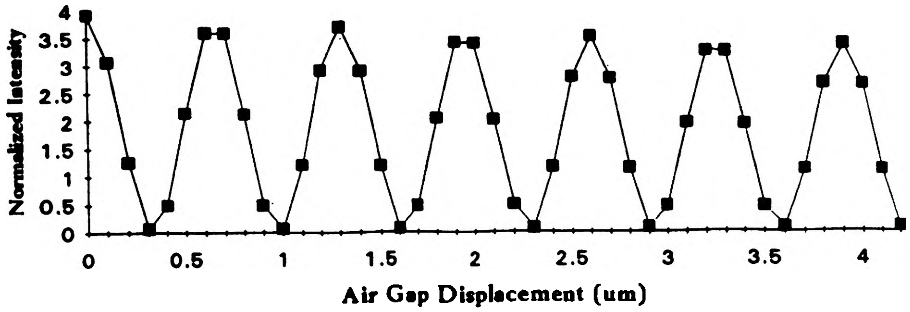

Figure 7. Theoretical Strain Gauge Intensity Output

This ideal fringe data verifies the approximations made in analyzing the Fabry-Perot cavity, and reaffirms the interferometer accuracy in measuring displacement to within one micrometer. The values obtained regarding displacement of two points can then be used to calculate strain for any material under test.

CONCLUSIONS

Fiber optic sensors for smart structures have many advantages over comparable electrical systems due to their small size, ruggedness, electromagnetic immunity, and compatibility with composite materials. These sensors are relatively easy to incorporate in composites during manufacture, and potentially can provide useful information about the structural integrity of complex materials.

An extrinsic fiber optic Fabry-Perot interferometer proved to be a very useful microdisplacement and strain sensor for use in smart structure applications. Sensor construction was simple, requiring a fiber Fabry-Perot cavity, directional coupler, laser diode, photo detector, and support electronics. The simple construction provided economy and ruggedness, while achieving good resolution up to at least 200 μm gap displacements at an accuracy of 1 μm.

By counting the number of intensity interference fringes detected due to a material deflection, the sensor gap displacement can be determined by a simple relation. This gap displacement can then be used to calculate material strain. Although accuracy of 1 μm was achieved in this experiment, higher precision may be possible using a more stable laser source.

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