Strain sensing using embedded optical fibers and radio-frequency interferometry

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ABSTRACT

An embedded optical fiber was used to measure the strain in a composite laminate. Strain was deduced form the induced propagation delay as measured by radio-frequency optical interferometry. The output of the optical sensor was found to follow the actual integrated average strain with some fluctuations which are attributed to polarization effects.

1. INTRODUCTION

In-situ dynamic strain measurements are fundamental for smart structures applications. Fiber-Optic Sensors have many advantages over other type of sensors, especially for those structures which use composite materials. Here the optical fiber can be embedded into the composite laminate with little effect to the laminate mechanical properties. In this paper we present a fiber-optic based sensor that measures the average longitudinal strain in a composite laminate. While many optical sensing techniques can be utilized for this purpose, we chose to measure the strain via the additional propagation delay induced by the straining force. Being interested in strains in the range of [0-3000] microstrain we preferred to use radio frequency (RF) interferometry over the much too sensitive optical interferometry. Sec. 2 describes the composite laminate and the optical fiber embedding process. The RF interferometer is presented in Sec. 3 together with the rest of the experimental set up. This is followed by the results (Sec. 4) and conclusions.

2. MANUFACTURE OF LAMINATES WITH EMBEDDED OPTICAL FIBERS

Laminates containing optical fibers were manufactured using conventional aircraft industry prepreg lay-up, vacuum bag and autoclave cure techniques. The test specimens are 600×100mm. four ply made of graphite/epoxy prepreg cloth. The optical fiber was embedded along the carbon fibers direction in between the center plies [Fig. 1]. The curing process incorporated cure and post-cure temperatures up to 185°C and pressures up to 7 bar.

During the heating phase of the cure process, the resin viscosity drops to a very low value prior to the start of gelation. Consequently, substantial resin flow occurs, usually into areas of the vacuum bag, and auxiliary materials within the bag, outside the area of the laminate proper. During the early stages of this work, it was found that this resin flow onto optical fibers extending from the area of the laminate caused embrittlement of the optical fibers to such an extent that demoulding and handling of the laminate without breaking the optical fibers was almost impossible. Accordingly, considerable effort was expended on developing methods for protecting exposed ends of optical fibers resin flow. In parallel, termination and connection systems were developed using modified components of standard optical fiber connectors embedded into laminates. These studies were reported in [5]. Similar problems have been reported by other workers, see e.g. [6]-[8] and various methods for their solution have been suggested.

In parallel, the effect of the high temperatures and pressures during the curing process on the integrity and optical performance of the embedded fibers was studied. It was established at an early stage of the work that acrylic jacketed fibers are unsuitable, since the jacket material is unstable at the cure conditions used. Accordingly, all the work described herein used polyimide jacketed fibers. X-radiography and micrography of laminates and optical transmission measurements demonstrated the integrity of the embedded polyimide jacketed fibers. An electrical resistive strain gauge was also attached to the face of the specimen for comparison.
3. THE RF INTERFEROMETER AND THE EXPERIMENTAL SETUP

The experimental set-up is shown in Fig. 2. A 2.5 GHz signal is split (at the splitter) and recombined at the mixer. While the reference arm of this RF interferometry is just a piece of coaxial cable, connecting the splitter with the local input of the mixer, the signal arm incorporates an optical transmitter, an optical receiver and the optical fiber. The RF signal modulates the intensity of the 1.3 µm laser. The modulated light propagates through the single-mode fiber and experiences a phase delay which is proportional to the optical length of the fiber.

At the receiver, the optical modulation is converted back to the electrical domain and the resulting delayed 2.5 GHz sine wave is mixed with its reference to generate an IF signal which is a function of the relative delay, τ, between the signal and reference arms of the interferometer:

\[ V_{out} = V_{IF} = A \cos(\omega_f \tau) \]  

We can always achieve zero output at the unstrained condition (where \( \tau = \tau_0 \)) simply by adjusting \( \omega_f \) such that \( \cos(\omega_f \tau_0) = 0 \). Under these conditions:

\[ V_{out} = A \sin(\omega_f \Delta \tau) \]  

where \( \Delta \tau(=\tau - \tau_0) \) is the additional propagation delay which accompanies the tensile strain. \( \Delta \tau \) is related to the strain by 9,10:

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\[ \Delta \tau = \frac{n_{\text{eff}} L}{c} \varepsilon \]  

(3)

Where \( \varepsilon \) is the strain \((\Delta L / L)\), \( L \) is the length of the sensing fiber, \( c \) is the light velocity in vacuum and \( n_{\text{eff}} \) (~1.146) is the effective refractive index after proper care has been taken of the effect of the strain on the refractive index. Limiting the measured strain to 3000 microstrain we find that \( \omega_p \Delta \tau \ll 1 \) so that Eq. (2) reduces to:

\[ V_{\text{out}} = A \frac{\omega_p n_{\text{eff}} L}{c} \varepsilon \]  

(4)

which predicts a linear relationship between \( V_{\text{out}} \) and \( \varepsilon \).

4. RESULTS

To check the set-up, a free optical fiber was strained and the results of Fig. 3 show excellent agreement with the predictions of Eq. (4).

Fig. 4 compares the optical measurements in the embedded fiber with those of a resistive strain gauge at the center of the laminate. The optical characteristics differ from the electrical ones in two aspects:

1. The slopes are different: While the optical sensor effectively measures the average strain, the resistive strain gauge produces only a local result. Also, the calibration of the fiber-optic sensor is based on the elasto-optical characteristics of the free fiber. The possible effect of the embedding process on these characteristics is under current investigation.

2. The optical result shows fluctuations when compared with the linear behavior of the resistive strain gauge response. We attribute these fluctuations to polarization mode dispersion which was induced into the fiber during the embedding process. See [11].

![Graph](image)

Fig. 3: The strained free fiber. The circles are measurement points and the straight line is based on Eq. (4) after \( A \) has been independently determined.
Fig. 4: The strained composite laminate: results for strain vs. loading from the optical and resistive sensors.

5. SUMMARY
The internal longitudinal strains were optically measured in a composite laminate containing an embedded fiber-optic sensor. Using RF interferometry strains of up to 3000 microstrains were measured. Some problems were identified and their solution is currently under further research.

6. REFERENCES
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