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Assessment of Mechanical Strength Degradation Using an Embedded Fiber-Optic Sensor

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A general method is presented for in situ assessment of mechanical strength degradation of materials or components using an embedded interferometric fiber-optic strain sensor. This method is based on the analysis of acoustic signature responses resulting from mechanical excitation of the subject under investigation. Acoustic signature responses are observed by monitoring light intensity changes resulting from the combination of light signals traveling through the embedded optical fiber (experiencing dimensional changes through vibrational excitation) and an external optical fiber. This paper discusses the fundamental aspects of the methodology and its potential investigational pathways and applications. A case study, addressing unobservable corrosion related degradation of aircraft fuselage lap joints is presented as an example for retrieving information and to demonstrate the correlations between material properties and fiber-optic interferometric measurements. The application of inverse method analysis for the interpretation of response signals is also discussed.

Keywords corrosion testing, failure analysis, nondestructive testing, mechanical testing

1. Introduction

As the nation's infrastructure ages (buildings, bridges, cables, overhead wiring, pipelines, and aircraft) the potential for catastrophic and costly events associated with material failure is becoming a topic of great interest (Ref 1-3). Prediction of the timing of these events is complicated by incomplete or missing knowledge concerning original conditions, maintenance cycles, and the effects of mechanical and environmental stresses over time. Methods of continuously detecting material degradation during normal usage and environmental exposures represent a potential solution to these concerns. This paper discusses a general method for the incorporation of fiber-optic sensors into structural components for the purposes of monitoring mechanical behavioral changes.

There have been several inspection techniques traditionally employed to monitor the degradation of material or component strength resulting from stress, fatigue, oxidation, corrosion, or a combination of these factors. The first and most frequently used is visual inspection. This method, however, only detects the surface manifestations of damage, such as crack formation, pitting, rusting or the build up of oxidation products. By the time such effects are observable, it is typical that structural integrity has been severely compromised (Ref 4). In addition, the presence of paints or sealants, used to provide protection from the environment, makes visual inspection difficult, if not impossible. Techniques for observations through the paint such as ultrasonic inspection and X-ray analysis come with their own set of limitations such as the problem of interpreting those features of signals that can be related to the level of degradation. Similarly, low- and high-frequency eddy current techniques can be degraded by the presence of paint or surface features not related to damage, and thus signal interpretation can again be difficult or misleading. X-ray radiography is generally cost prohibitive and proper interpretation of the radiograph can be limited by the subjective judgment of the observer. Besides the limitations of cost and signal interpretation, there remains the problem of relating the information of visual and enhanced visual examinations directly to changes in bearing strength. Moreover, in general, these methods have not been adapted for continuous assessments as a structure or component is being used. This represents a serious limitation in that it is not possible to account for the complex set of environmental and mechanical factors that a structural component is likely to encounter during its lifetime and thus to predict failures based on information acquired by intermittent assessment techniques.

The use of fiber-optic based sensors for the detection of changes in the physical characteristics of surfaces and interfaces is being developed for a wide range of applications including corrosion monitoring, analysis of surface interactions between chemical and biological species, and monitoring of materials deterioration correlated with either damage or failure of a system or structure (Ref 5-16). The general structure of fiber-optic based sensors is such that they are well-suited for the distributed sampling of system responses over relatively large sets of both spatial locations of the sensor and changes in physical characteristics of the system. The wealth of

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information contained in these responses can be mined for characteristics of the system either through a direct or inverse-problem approach. In the direct-problem approach, the characteristics of the detected signal are predicted using either an explicit numerical solution to equations of electromagnetic wave propagation in materials based on different formulations or an explicit physical model based on analytical representations of the intensity distribution within the fiber-optic sensor system for a specific geometry. The direct-problem approach requires an a priori knowledge of the physical characteristics of the fiber-optic sensor and of its coupling to the environment under detection. Further, this approach requires knowledge of the electromagnetic response properties, as a function of wavelength, of the materials making up the sensor system. In the inverse-problem approach, the characteristics of the detected signal are predicted using a model representation whose form is relatively convenient for the adjustment of parameters. Parameters are adjusted according to experimental data concerning a field quantity, e.g., intensity or wavelength, at various locations that are sufficiently distributed either spatially throughout the environment under detection or parametrically relative to the parameter space representing a specific characteristic of the system. The model representations adopted for an inverse-problem approach can be based on parametric formulations that range from those which include detailed descriptions of the underlying physical processes to mathematical-function forms that are relatively simple. It is noted therefore that an inverse-problem approach to sensing using optical fibers can be applied via any conveniently adjustable parametric representation of the field quantity to be detected. This follows since any "well-behaved" function representing sufficiently distributed field values, which have been obtained from measurements, can be adopted as an accurate interpolation function for regions of interest.

Direct-problem and inverse-problem formulations possess an interrelationship that is important with respect to analysis based on the inverse-problem approach. An aspect of this interrelationship is that all direct-problem based parametric representations may be adopted for inverse analysis, and that in general, direct-problem analyses can be interpreted as inverse-problem analyses. This interrelationship implies that a reasonable starting point for the formulation of an inverse-problem based method of analysis is to adopt a direct-problem based physical representation as an assumed model for further modification according to the characteristics of the experimental data concerning the field quantities of interest, e.g., modulation of intensity or wavelength in the case of sensing using optical fibers. Ref 5, as an example, illustrates the use of an inverse-problem methodology to study surface degradation using fiber-optic reflectance responses. The case study analysis presented here, using an embedded fiber-optic strain sensor, represents a qualitative inverse analysis of lap joint degradation. For this inverse analysis, the direct-problem representation of a plate structure, whose vibrational modes undergo change as a result of changes in stiffness due to corrosion, is assumed as a starting point.

The approach presented here for assessing the mechanical condition of a material or component involves measurements of the characteristic vibrational modes resulting from the application of a controlled mechanical stress. These vibrational modes are accessed through observations of changes in the intensity of light collected after passing through an attached fiber-optic cable (sensor). Changes in intensity signatures (correlated to displacements) could then be used to detect and assess a loss of stiffness or mechanical integrity resulting from any form of damage. To be a feasible technique the sensor used for detection of mechanical behavior changes must be applied to, or incorporated into, the structure in the critical locations. What is required for a practical embedded sensor is good sensitivity, flexibility, low-cost, and the ability to sense changes over an area rather than at just a point. Additionally, the sensor must be robust so that it can survive the same environmental conditions, which produce degradation in the joint. An example of a sensor technology that has most of these attributes is the fiber-optic interferometric strain sensor which has historically been used in submarine hull structures for acoustic sensing, and which is adopted as the basis of our methodology (Ref 17).

Fiber-optic based sensors are generally categorized according to the method of detection used to couple changes in the light transmitted through the optical fiber to changes in a given physical characteristic of the system. These methods depend on the fiber-optic sensor geometry and measurements of either intensity loss, or modulated reflection or transmission at an interface. A sufficiently complete summary of the different categories of fiber-optic sensors is given in Ref 8 within the context of fiber-optic strain sensors. The present paper presents a fiber-optic strain sensor capability that can be applied in principle with any type of fiber-optic sensor geometry, and that establishes a correlation between level of mechanical degradation and intensity loss as a function of time.

The next section describes an experimental case study performed to observe vibrational responses using a fiber-optic interferometric sensor to detect vibrational responses to mechanical excitation of a metal joint and to assess the sensitivity of these changes to its mechanical condition.

2. Case Study of Detection of Mechanical Degradation in Aircraft Lap Joints

This section illustrates the capabilities of a fiber-optic strain sensor for detecting changes in mechanical properties. Accordingly, an experimental procedure and results of measurements that have been conducted on a component simulating aircraft lap joint configurations are summarized. Further details of this experimental procedure have been reported elsewhere (Ref 18). In addition to confirming correlation between mechanical behavior and fiber-optical response, this example also demonstrates that fiber-optic response can be correlated with damage taking place in areas that are not observable by visual inspection.

2.1 Experimental Technique

Prototype lap joints were fabricated by partially overlapping two aluminum sheets and attaching them with threaded screw fasteners arranged in a rectangular pattern (Fig. 1). This rivet pattern is similar to that used in fuselage construction (Ref 2). Local stiffness and vibratory behavior of the joint could be varied accordingly by loosening or tightening the threaded fasteners. The loosened-position simulates the degradation of the joint due to fastener fatigue, mechanical assault, or corrosion processes. A commercially available communications fiber was used as the sensing fiber. The fiber-optic path, or "pattern", chosen for the experiments was one in which the

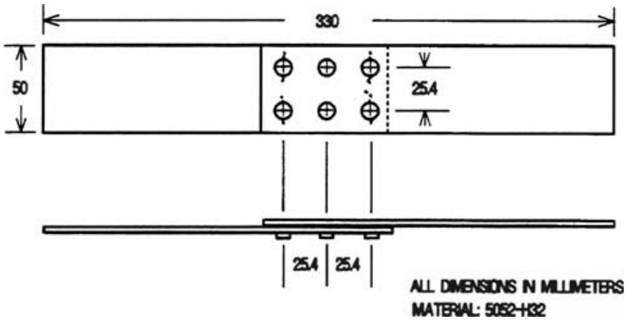

Fig. 1 Schematic representation of prototype lap joint

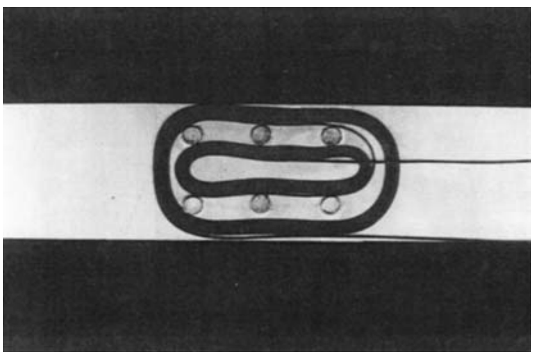

Fig. 2 Photograph of the fiber-optic strain sensor pattern applied to the prototype lap joint

fiber was routed near the fasteners several times (Fig. 2). The total fiber length in the pattern was 8 m. Also attached to the joint was an accelerometer for comparison with the fiber-optic strain sensor.

The fiber-optic interferometric strain sensor used consists of two fibers, the sensing fiber applied to the model or prototype lap joint, and a reference fiber that is part of the readout instrumentation. Light having a 1.3 μm wavelength obtained from a Nd:YAG glass laser is split by a 2×2 fiber coupler and transmitted to the sensing fiber and the reference fiber (Fig. 3). After traversing these two fibers, the two light beams are recombined at another fiber coupler and detected by a photodiode. This detector senses changes in the light intensity downstream of the recombination point. Any change in the strain applied to the sensing fiber changes the phase of the light propagated in this fiber. After the recombination of the two light beams, this phase change results in a light intensity change at the detector. Thus, any change in the length of the sensing fiber will modulate the light power at the photodiode. For sensing fiber length changes less than half the wavelength of the laser light (1.3 μm), a continuously decreasing change in intensity with strain is observed. For larger strains, however, which produce length changes greater than the laser light wavelength, a periodic intensity change will be observed as the light passes in and out of phase at the recombination coupler.

For the experiments reported here, all length changes of the sensing fiber are less than the wavelength of the laser light, i.e., 1.3 μm. In order to avoid the problem of deconvoluting the signal for frequency multiplying due to fiber length changes in excess of a wavelength, a piezoelectric actuator was used to enable a controllable low-level of vibration in the model lap

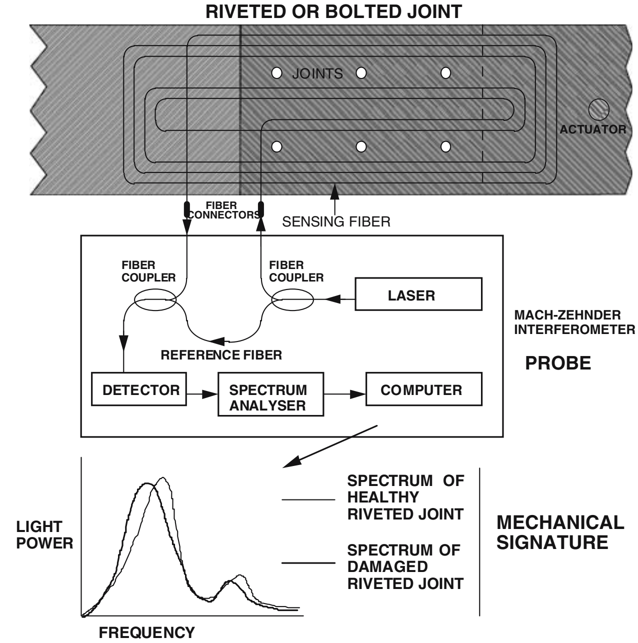

Fig. 3 Schematic diagram of the experimental arrangement

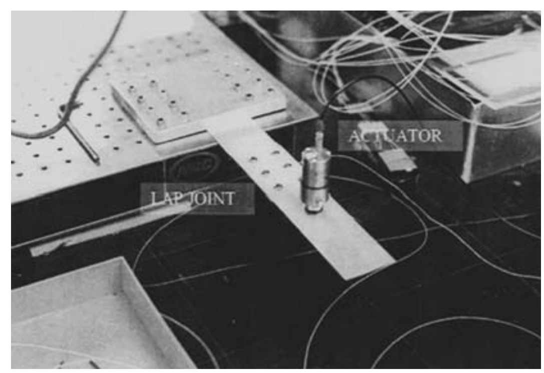

Fig. 4 Photograph of the experimental arrangement. The fiber-optic array is positioned on the lower-surface of the joint. An accelerometer, typical of those used in structural vibration analysis, is attached for comparison with the output of the fiber-optic sensor

joint (Fig. 4). The lap joint is clamped at one end and vibrated as a free cantilever beam. The entire assembly, including the reference fiber, is mounted on an isolation table in order to reduce sensing of stray vibrations from the laboratory environment during an experiment.

In principle, the fiber-optic sensor has a relatively high-sensitivity in that it employs phase modulation of light. Accordingly, the minimum detectable length change is a function of the wavelength of light used and of the sensing fiber length. The minimum detectable strain can be calculated from the minimum detectable phase change that, under ideal laboratory conditions, is 10^{-6} radians (Ref 5). Since the laser wavelength of 1.3 μm corresponds to 2π radians, a minimum length change of 10^{-13} m can be detected under ideal conditions. In terms of strain, a 1 m sensing fiber could then detect strains on the order of 10^{-13} whereas a 100-m fiber could detect strains on the order of 10^{-15}. In the experiments discussed the fiber length is 8 m, which results in a minimum detectable length change of around 10^{-14} m assuming a uniform strain field under the fiber. In terms of strain, therefore, the sensitivity is adjustable depending on the total length of the fiber-optic strain sensor exposed to the strain field in the structure to which it is applied. It should be noted, however, that the extremely small displacements that the technique is capable of sensing, on the order of atomic dimensions, are not going to be utilized in practical structural sensing applications.

The stiffness of the model lap joint was varied by loosening the two fasteners nearest the clamping point. The other four fasteners remained tight. The attached actuator, inducing excitation of the lap joint, scanned over a frequency range of 0-10 kHz in both the "fasteners loose" and "fasteners tight" conditions. The signals from both the photodiode and the accelerometer were captured using a HP3582A frequency analyzer. These signals were recorded as 20 Log *V*, where *V* is the voltage output of the sensors. The data from this frequency analyzer were downloaded into a computer for comparison of the different vibrational response spectra obtained from the excited lap joint structure.

The sensing fiber integrates the strain along its length. Due to its high-geometrical flexibility and very small size, the sensing fiber can be routed several times around the area of interest. These attributes result in a very high-sensitivity since it is proportional to the sensing fiber length. In contrast, conventional resistive strain gages cover only a very small area. When the joint is excited by the actuator, the strains in the sensor fiber changes its length. This produces the interference at the second fiber coupler that is detected by the photodiode. The signal from the photodiode was processed by a spectrum analyzer in order to construct a curve expressing frequency as a function of intensity (20 Log *V*), as the actuator scanned through the selected excitation frequency range. This curve can be adopted for the extraction of those "signatures" that are observed to be sensitive to small changes in the stiffness of the lap joint. Comparison of changes in such signatures can then be used as a diagnostic tool to detect changes in the mechanical behavior of the lap joint produced by damage from corrosion, fatigue, and fastener degradation. It is significant to note that similar vibration signature analysis techniques are used for the conditioned based maintenance of rotating machinery (Ref 2, 19, 20).

Note: It is important to note that for the purpose of detecting changes in the mechanical behavior of actual lap joints during the early stages of corrosion and fatigue damage, it is the integrated sensitivity over the length of sensing fiber that provides for detection of strain.

2.2 Results

The results of the case study investigation are shown in Fig. 5-9. Shown in Fig. 5 are characteristic vibrational signatures that were obtained by scanning the actuator from 0 to 1 kHz for the "fasteners tight" and "fasteners loose" conditions. Two features are readily apparent when comparing these response curves. Referring to Fig. 5, it can be noted that at approximately 300 Hz, a peak shift to a lower-frequency is observed for the "fasteners loose" configuration, and at 600 Hz, a new peak appears in the "fasteners loose" configuration. What is interesting to note here is that the accelerometer is does not detect the effects of the very small accelerations produced by the actuator (Fig. 6). The fiber-optic sensor, however, is able to detect extremely small displacements in the joints.

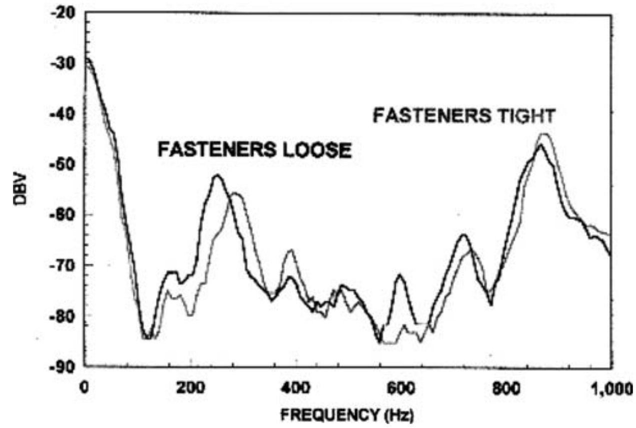

Fig. 5 Comparison of fiber-optic strain sensor responses observed in the "fasteners tight" and "fasteners lose" modes

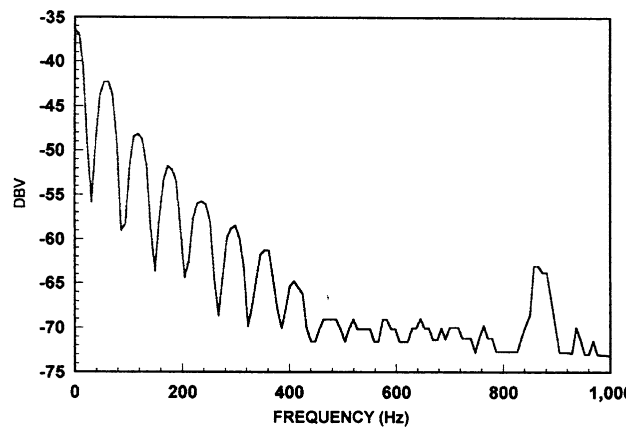

Fig. 6 Accelerometer responses for vibratory signals applied in the 0-1 kHz frequency range

As an illustration of the capability of a fiber-optic strain sensor to detect extremely small changes a 0-500 Hz scan was performed (Fig. 7). In this regime the accelerometer does not detect any accelerations but the fiber-optic strain sensor readily detects changes in joint behavior as a peak shift to a lower-frequency. At higher frequencies (greater than 500 Hz) the accelerometer, typical of instrumentation used in structural vibration analysis, can detect changes in joint vibration signature. However, these changes are only symptomatic of the point at which the actuator is positioned (Fig. 8). The fiber-optic strain sensor is also useful at the higher frequencies up to 10 kHz (Fig. 9) and the measurements reflect vibratory changes occurring in a broad field occupied by the fiber-optic pattern. From this study, it can be seen that the fiber-optic technique has a greater dynamic range than the accelerometer and senses over a broader range, i.e., strains in the joint, as opposed to the vibratory point changes detected by the accelerometer.

Note: The analysis presented above demonstrates a qualitative inverse analysis of lap joint degradation using an optical fiber sensor. Quantitative inverse analysis can be established by associating with the response signatures a set of feature variables that can be correlated with specific physical characteristics of the lap joint structure (see Ref 5

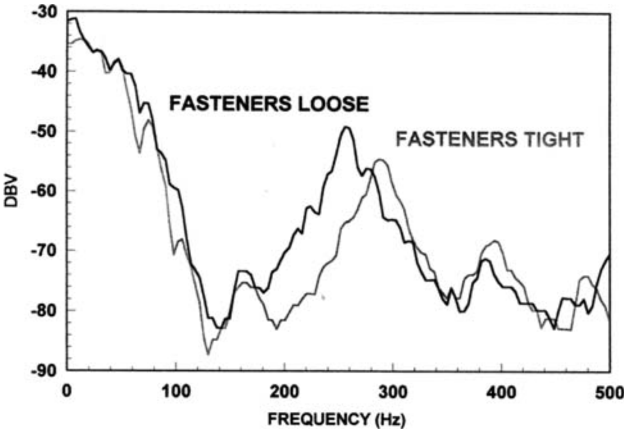

Fig. 7 Comparison of fiber-optic strain sensor responses in the ''fasteners tight'' and ''fasteners loose'' modes for vibratory signals applied in the 0-500 Hz frequency range

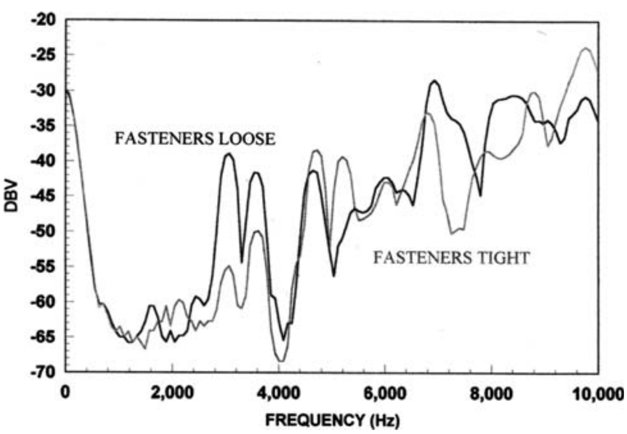

Fig. 8 Comparison of accelerometer responses in the ''fasteners tight'' and ''fasteners loose'' modes for vibratory signals applied over a 0-10 kHz range

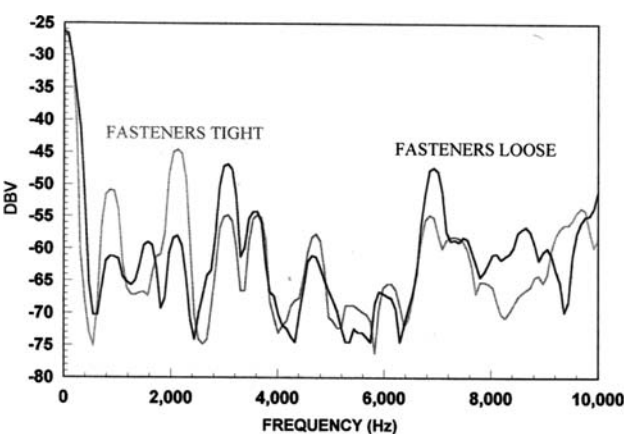

Fig. 9 Comparison of fiber-optic responses observed in the ''fasteners tight'' and ''fasteners loose'' modes for vibratory signals applied over a 0-10 kHz range

for example). Such feature variables could be, for example, the locations and widths of peaks of response curves that can be related through a mechanical model of plate structures to the vibrational response modes of a given lap joint structure.

3. Conclusions

The fiber-optic strain sensor presented here can be adopted for the detection of small changes in mechanical behavior when used to capture signatures associated with the vibration frequency spectrum of a functional component. Inverse analysis of signature changes can be used in principle to determine the level of the damage within a functional component. In principle, the fiber-optic strain sensor can embedded into structures or mechanical components for the purposes of monitoring change in mechanical integrity, regardless of the cause of this change.

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