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ASSESSING THE HEALING OF MECHANICAL STRUCTURES THROUGH CHANGES IN THEIR VIBRATIONAL CHARACTERISTICS AS DETECTED BY FIBER OPTIC BRAGG GRATINGS

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1. INTRODUCTION

The need for early damage detection in mechanical elements and structures permeates most areas of engineering. This necessity has led to the development of a variety of experimental techniques designed to monitor the structural health of mechanical systems, at both local and global scales. A global approach that has received increased attention during the last decade is that based on the detection of damage through changes in the dynamical characteristics of the structures [1–3]. As faults develop, the changes induced on the stiffness and inertial properties of the structure modify its modal parameters such as frequencies and mode shapes. Conversely, when the structure is repaired, its physical parameters and, consequently, its modal parameters, should return to values close to those characterizing the original structure. This observation allows for the possibility of on-line monitoring of the healing process by measuring the vibrational characteristics of the mechanical system as a function of time.

This communication presents a simple experimental set-up where real-time assessment of the degree of healing is achieved through measurements of the resonant frequencies of the system with a fiber optic grating. The potential of the proposed set-up is demonstrated for the case of a cracked cantilever beam that is repaired using an epoxy resin. It is shown that the combination of fiber optic gratings and vibration analysis constitutes a promising approach in the development of practical probes for on-line monitoring of curing processes.

2. FIBER OPTIC BRAGG GRATINGS

Fiber optic sensors have become an alternative to traditional methods of sensing in several fields, particularly in connection with the need of distributed sensing for the development of smart structures. The advantages of fiber optic sensors are well known, and include their small size and weight, environmental ruggedness, immunity to electromagnetic interference, and high sensitivity and embeddibility [4, 5]. Among the wide variety of fiber optic sensors developed to date, fiber Bragg gratings are one of the most favored solutions in applications where multiplexing is sought, since they are easily multiplexed by connecting

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them in series in a single span of fiber [6]. Grating-based sensors have shown the potential to impact a number of applications where quantities such as strain, temperature, load and vibration need to be measured. In the particular case of vibration measurements, they have been proposed as a tool for structural shape sensing [7]. From the point of view of cure monitoring, Bragg gratings have been embedded in epoxy composites to make *in situ* measurements of the strain level in the optical fiber induced by the curing process [8].

A fiber Bragg sensor is based upon the inscription of a periodic variation of the index of refraction in the core of a single-mode optical fiber. When a relatively broadband optical source is coupled into the fiber, a narrowband portion of the spectrum is reflected by the grating at a characteristic wavelength, called the Bragg wavelength, which depends upon the period of the grating. Under the effect of an external agent such as strain or temperature, the period of the index modulation will change, therefore, shifting the wavelength of the reflected peak. The magnitude of the axial strain or temperature change can be estimated using expressions that relate them to the wavelength shift through the photoelastic constant and the coefficient of thermal expansion of the fiber material. Several techniques are available to obtain accurate values of the strain and temperature changes affecting the fiber [6]. In the simple case presented in this communication, however, we do not measure the actual values of these parameters but rather sense their relative variation as a function of time.

3. DESCRIPTION OF THE EXPERIMENTAL SET-UP

The set-up is schematically shown in Figure 1. The aluminium cantilever beam used in the experiments was 400 mm long, 9·55 mm high and 9·60 mm thick. A 7·4 mm deep crack was cut at 17 mm from the clamped end using a 2·5-mm end mill. For the experiment described herein, the cut was filled with a two-component commercial epoxy resin with a specified setting time of 10 min. The cantilever beam was forced into oscillation by a 15-mm-diameter, 20-turn coil weighting 2·8 g attached to the free end of the beam. The coil was placed in the field of a permanent magnet and excited with a square voltage pulse. The 25-mm long grating was glued to the lower surface of the beam at 50 mm from the clamped end.

The optical system used to interrogate the fiber grating is depicted in Figure 2. Light from a laser diode centered at 1·3 μm (Type: Mitsubishi 725B8F) was focused into a 2×2, $\frac{50}{50}$ split ratio fiber coupler (Type: Thorlabs 10202A-50). One output was connected to the Bragg grating (Type: Innovative fibers FBG-1300), which was centered at 1·30 μm with a reflectivity of 80% at the center wavelength and had a bandwidth of 0·2 nm. Since the laser diode had an emission bandwidth larger than that of the grating, changes in the period of the grating produced by the strain translated into measurable changes in the intensity of the light reflected back. The intensity of the light reflected from the grating was monitored with a high-speed InGaAs detector (type: Thorlabs DET410) whose output signal was acquired by a 100 MHz, 1 Gs/s digital oscilloscope (type: Tektronix TDS220).

To perform the measurements, the coil was excited with a short square voltage pulse and the oscilloscope was triggered using the falling edge of the pulse. The first few amplitude oscillations of the beam were acquired by the oscilloscope and downloaded to a PC for further processing. Prior to gluing the grating to the beam and filling the cut with the epoxy resin, a 25-mm portion of the fiber not containing the grating was attached to the beam to register the signal that could be expected from stray bending effects on the fiber. Figure 3 shows that the oscillatory signal sensed by the photodiode is produced by grating when subjected to strain, and that no noticeable contribution comes from straining the fiber itself.

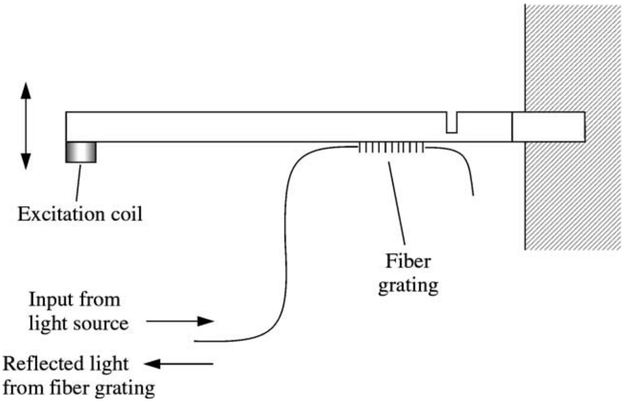

Figure 1. Experimental set-up.

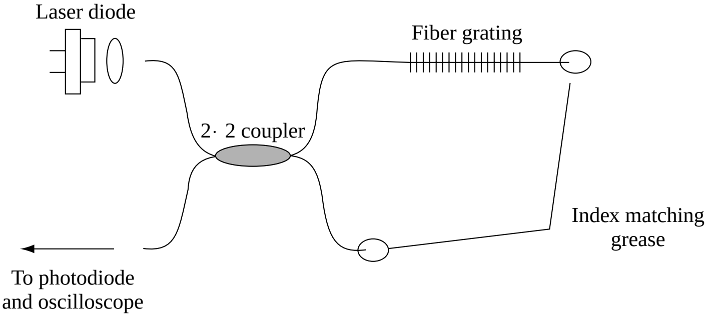

Figure 2. Details of the optical detection system.

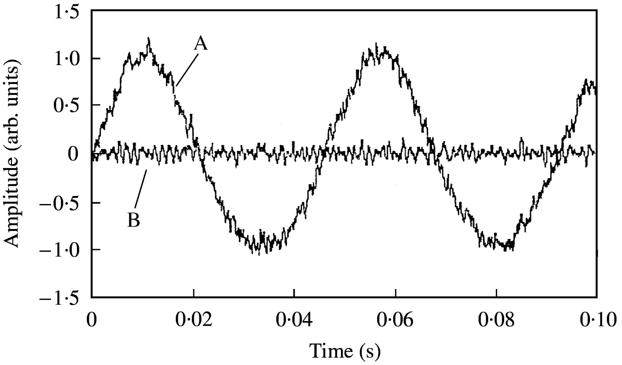

Figure 3. Photodiode signal as displayed by the digital oscilloscope. Trace A corresponds to the signal registered when the 25 mm long Bragg grating is attached to the beam. Trace B is the signal obtained when a 25-mm long section of the fiber not containing the grating is attached to the beam.

4. RESULTS AND DISCUSSION

Right before starting the process of acquisition, the two-component epoxy was mixed and the cut was filled. To monitor the process of curing, measurements were taken every 1·5 min. The resulting waveforms were downloaded and a damped sine function was fitted to the data to extract the value of the frequency of the first vibrational mode. The results of the measurements are displayed in Figure 4. Due to the presence of the deep crack close

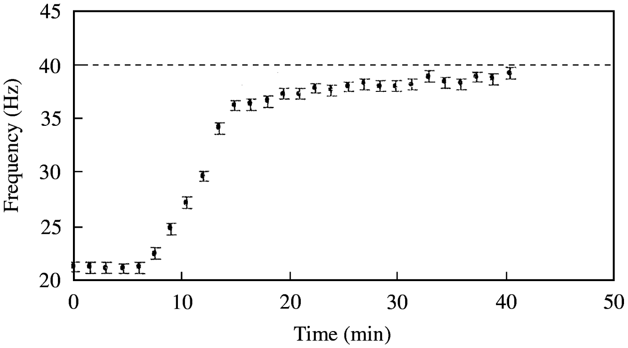

Figure 4. Frequency of the first resonant mode during cure. The dotted line indicates the long-term value of the frequency measured 24 h after mixing the epoxy resin.

to the clamping, the frequency starts at approximately 21 Hz, less than half of that corresponding to the undamaged beam (46·5 Hz) [9]. During the first 7–8 min after mixing, no significant changes are observed in the value of the resonant frequency. A visual inspection of the adhesive shows that, for this time interval, the viscosity remains low. Following this initial period, the value of the frequency increases dramatically, reaching a value of approximately 36 Hz at 15 min. This sudden increase coincides with a noticeable viscosity rise, which usually indicates the formation of a 3-D molecular network in a process known as gelation. After 20 min, the value of the frequency continues to increase slowly up to a long-term value of approximately 40Hz. Since the mechanical properties of the cured adhesive do not match those of the aluminum, it is observed that the long-term value of the resonant frequency remains lower than that of the undamaged beam.

In summary, the use of a combination of fiber gratings and vibration analysis for healing monitoring has been presented. When applied to the simple case of a cracked cantilever beam repaired with epoxy resin, the technique clearly reveals the temporal evolution of the curing process in the adhesive through the growth and change of the value of the first resonant frequency. It is felt that this approach may prove to be useful for monitoring healing processes in mechanical elements and structures. From a different perspective, the technique outlined herein could have potential application in the assessment of healing of long, fractured bones, where it has been shown that the variation of natural frequencies may eventually constitute an indication of the healing process [10]. Finally, and from another point of view, this simple experimental set-up (or even a simpler version where the value of the vibration amplitude is taken directly from the excitation coil) could be useful in the mechanical characterization of adhesives.

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