Simultaneous Measurement of Strain, Temperature, and Vibration Frequency Using a Fiber Optic Sensor

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Abstract

In this paper, a novel technique for simultaneous measurement of strain, temperature, and vibration for structural health monitoring is demonstrated using a fiber optic sensor system, which combines both a wavelength-swept fiber laser (WSFL) system and a laser diode system using a wavelength division multiplexer. An aluminum beam was placed in a thermal chamber and the efficiency of the constructed system was validated for the simultaneous measurement of the strain, temperature, and vibration characteristics. A fiber Bragg grating (FBG)/extrinsic Fabry-Perot interferometer (EFPI) hybrid sensor system with WSFL was used for the strain and temperature measurement, while the EFPI sensor in the hybrid sensor operated by a laser diode simultaneously measured the vibration characteristics of the beam.

Keywords: Fiber optic sensor, Fiber Bragg grating, Extrinsic Fabry-Perot interferometer, Strain, Temperature, Vibration, Wavelength-swept fiber laser.
1. Introduction

A multi-functional sensor that can measure multiple parameters offers significant economic advantages and end-user appeal. Furthermore, the ability to monitor the multiple parameters simultaneously would be of significant benefit to material and structural engineers. For assuring the integrity of structures such as aircrafts and satellites, it is desirable to simultaneously monitor the strain, temperature, and vibration applied to them in real-time.

Fiber optic sensors (FOSs) have many advantages such as immunity to electromagnetic interference (EMI), high strain sensitivity and high temperature resistance, small dimensions, geometric versatility, etc. Concurrent with rapid progress in the development of FOSs, the potential of wide applications and their use to measure various physical parameters has been reported. For the measurement of multiple parameters using a single FOS, most research has been conducted to measure two parameters such as strain and temperature[1-3], and strain and failure[4-5]. However, there has been little work on the measurement of more than 3 parameters using a single fiber optic sensing element. Rao and Henderson et al.[6] performed the simultaneous measurement of static-strain, temperature, and vibration using a wavelength-multiplexed in-fibre-Bragg-grating/fibre-Fabry-Perot sensor system. Since this system was composed of only three fiber Bragg gratings (FBGs), the compensation of the temperature effect was not easy.

In this paper, we constructed a novel measuring system to monitor strain, temperature,
and vibration simultaneously for structural health monitoring. The measuring system was composed of two optical systems, a FBG/EFPI hybrid sensor system using a wavelength-swept fiber laser, which is a broadband source, and the EFPI sensor in the hybrid sensor operated by a laser diode, which is a narrow band source. In order to integrate the two systems to one FOS, they were combined by a wavelength-division multiplexer. We performed simultaneous measurement of the thermal strain, temperature, and vibration of an aluminum beam placed in a thermal chamber using the constructed measuring system.
2. FBG/EFPI hybrid sensor

In our work, a FBG/EFPI hybrid sensor was used to measure strain, temperature, and vibration simultaneously. Figure 1 is a schematic diagram of the FBG/EFPI sensor. A FBG is encapsulated in a silica capillary tube to be isolated from the external strain. The EFPI cavity was formed between two cleaved fiber ends inserted into the capillary tube. The FBG is in a strain-free condition and is only affected by the temperature change within the capillary tube, while the EFPI is affected by both thermal and mechanical strains. When a broadband light illuminates this sensing element, the reflected spectrum of the Bragg grating element has a narrow bandwidth with high reflectivity, whereas a sinusoidal wave with a fraction of the total optical power is reflected through the EFPI sensor, a low finesse interferometer. Also, when a narrow band laser illuminates this sensor, we can obtain the interferometric signal due to the change of cavity length of the EFPI in time domain. In our previous work, we analytically derived the relationship of strain and temperature to sensor outputs by the following procedure [3].

For a FBG, the Bragg condition is given by $\lambda_B = 2n_e \Lambda$, where $\lambda_B$ is the Bragg wavelength of FBG, $n_e$ is the effective index of the fiber core, and $\Lambda$ is the grating period. The shift of Bragg wavelength due to the strain and temperature can be expressed as

$$\Delta \lambda_B = \lambda_B \left[ (\sigma_f + \xi_f) \Delta T + (1 - p_e) \varepsilon \right]$$

(1)
where $\alpha_f$ is the coefficient of thermal expansion (CTE), $\xi_f$ is the thermo-optic coefficient, and $\xi_e$ is the strain-optic tensor of the optical fiber. For the FBG/EFPI sensor, because the FBG in a glass capillary tube is in a strain-free condition, $\varepsilon = 0$, (1) can be simplified in terms of only the temperature change as

$$\Delta \lambda_n = \lambda_n (\alpha_f + \xi_f) \Delta T.$$  

(2)

Therefore, we can measure the temperature change from the wavelength shift as

$$\Delta T = \frac{1}{\alpha_f + \xi_f} \frac{\Delta \lambda_n}{\lambda_n}.$$  

(3)

The response of the absolute EFPI(AEFPI) sensor comes from the thermal strain as well as the applied strain of a structure. When perfectly bonded to a structure, the thermal expansion of the sensor is constrained to take on the CTE of the host structure. Therefore, the thermal expansion of a FOS bonded to or embedded in a material becomes that of the structure itself. The cavity length, $d_i$, at any measuring instant can be measured from the peaks of the reflected spectrum as

$$d_i = \frac{m \lambda_i \lambda_2}{2(\lambda_2 - \lambda_1)} \quad i = 0, 1, 2...$$  

(4)
where $\lambda_1$ and $\lambda_2$ are two wavelengths that are $2m\pi$ out of phase and $m$ is an integer. $i$ is the number of the measuring instant, and in the case of initial state, $i=0$. If the EFPI sensor has a gage length of $L$, the applied strain can be expressed as

$$\varepsilon = \frac{d_2 - d_0}{L} = \frac{\Delta d}{L}$$

(5)

where $\Delta d$ is the change of cavity length, and $d_2$, $d_0$ are the final and initial cavity lengths, respectively. When temperature change and strain are applied to structures with an embedded or attached FBG/EFPI sensor, the lengths of internal optical fibers in the capillary tube are changed with their CTE by temperature change only while an external capillary tube is subject to both thermal and mechanical strains of structures. Therefore, we can measure the total strain applied to a structure through the variation of a reflected spectrum by the difference of length change between the sum of two internal fibers in the tube and the capillary tube. The strain measured from the EFPI interferometric signal, $\varepsilon_{mea}$, can be described by

$$\varepsilon_{mea} = \varepsilon_{tot} - \varepsilon_{f,T} = \frac{\Delta d}{L}$$

(6)

where $\varepsilon_{tot}$ is the sum of the mechanical and thermal strains of a structure, and $\varepsilon_{f,T}$ is the thermal strain of the internal optical fibers. We want to obtain the total strain of the structure, that is, the strain of the capillary tube. From (6) we can obtain the equation for total strain as
\[
\varepsilon_{\text{tot}} = \frac{\Delta d}{L} + \varepsilon_f \cdot \frac{L - d_0}{L} \cdot \alpha_f \cdot \Delta T .
\]  

(7)

Substituting (3) into (7) leads to

\[
\varepsilon_{\text{tot}} = \frac{\Delta d}{L} + \frac{L - d_0}{L} \cdot \frac{\alpha_f \cdot \Delta \lambda_T}{\alpha_f + \varepsilon_f} \cdot \lambda_T.
\]  

(8)

By combining (3) and (8), we can yield the relationships of the sensor outputs to measurands as

\[
\begin{bmatrix}
\Delta d \\
\Delta \lambda_T
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{L} & L - d_0 & \frac{\alpha_f}{L} & \frac{1}{\lambda_T} \\
0 & \frac{1}{\alpha_f + \varepsilon_f} & \frac{1}{\lambda_T}
\end{bmatrix}
\begin{bmatrix}
\Delta d \\
\Delta \lambda_T
\end{bmatrix}
\]

(9)

From (9), it should be noted that the characteristic matrix of the sensor could be determined by sensor specifications such as gage length, initial cavity length, the Bragg wavelength of FBG, and the CTE and thermal-optic coefficient of the optical fibers. The strain and the temperature can be easily determined by measuring the change of cavity length for the strain and the wavelength shift for the temperature. Hence, we can simply generate the matrix with known specifications of sensors using (9) and measure directly
and simultaneously the strain and the temperature of a structure. In our previous work [3], we verified the validity of the proposed relationship, (9), experimentally.
3. Experiment Details

3.1. Fabrication of fiber optic sensor

A 10 mm long FBG was encapsulated in a silica capillary tube (140/300 µm) to be isolated from the external strain. The EFPI cavity was formed between the fiber end face near to the FBG and a gold-coated fiber end surface inserted into the opposite end of the capillary tube. Specifications of the sensor are shown in Table 1. Substituting specifications of the sensor in Table 1 into (9), we can obtain analytically the components of the characteristic matrix of the sensor, as shown in Table 2.

3.2. Wavelength-swept fiber laser

A wavelength-swept fiber laser (WSFL)[7], a broadband source, was used to interrogate the FBG/EFPI sensor. Figure 2 shows a schematic of the configuration of the WSFL. The WSFL was in a unidirectional ring configuration with isolators, a 3-dB output coupler, and an Er$^{3+}$-doped fiber pumped by a laser diode at 980 nm. An F-P tunable filter was used as the intracavity scanning filter and had a 3-dB bandwidth of 0.27 nm and a free spectral range of 58 nm. We modulated the F-P filter with a triangular waveform to produce a wavelength sweep over 40 nm from 1525 to 1565 nm at a 200 Hz repetition rate. The output power of the WSFL was over 1000 times as large as that of the amplified spontaneous emission (ASE) of an LD-pumped Er$^{3+}$-doped fiber (EDF) which is usually used for the light source in a FBG sensor system [8].
3.3. Experimental apparatus and method

The experimental arrangement is depicted in Fig. 3. As shown in Figure 4, a FOS was attached on the top surface of an aluminum beam and a piezo-ceramic actuator was attached on the bottom surface of the beam. The aluminum beam was clamped at one end and placed in a thermal chamber. The thermal strain and temperature of the beam were measured along the elevation of the inside temperature of the thermal chamber using the FBG/EFPI sensor system. Also, vibration due to the piezo-ceramic actuator controlled by a function generator was detected using the EFPI sensor system, which consisted of a laser diode, a photo-detector, an isolator, and a 3-dB coupler.

The measurement system for the simultaneous measurement of the strain, temperature, and vibration, consisted of two parts. One was the FBG/EFPI sensor system[3], which included the WSFL as the light source, for the simultaneous measurement of strain and temperature, and the other was the EFPI sensor system, which included the laser diode, for the vibration measurement. The wavelength range of the output of the WSFL was from 1525 nm to 1565 nm and the output wavelength of the laser diode was 1305 nm. In order to apply these two lights to single FOS, two sensor systems were combined by a 1310/1550 wavelength division multiplexer. Since the wavelengths of the two sources were different, the lights of two sources did not interfere with each other. The reflected light from the sensor was split to the FBG/EFPI sensor system (1550 nm port) and the EFPI sensor system (1310 nm port) through the wavelength division multiplexer.

The signals detected by the FBG/EFPI sensor system were acquired by a computer
through the A/D converting board at 2-minute intervals. From the acquired data, the strain and temperature were calculated, displayed, and saved in real-time by the signal processing program written in LabView software. The signal detected by the EFPI sensor system and the actuating signal of the function generator were acquired by a computer through an oscilloscope. The frequencies of signals measured by the FOS were obtained by fast Fourier transform (FFT) and compared with the actuating frequencies of the piezo-ceramic actuator controlled by the function generator.
4. Experimental Results and discussions

Figure 5 shows the result of the strain and temperature measurement of the aluminum beam using the FOS. The thermal strain of the aluminum beam linearly increased with increasing temperature. Since a strain of about 1500 µε occurred during the temperature elevation from 25 °C to 90 °C, we can determine the coefficient of thermal expansion of the aluminum beam to be approximately 23×10⁻⁶/°C.

Figure 6 illustrates the results of the vibration measurement of the beam using the FOS. In the figures, the small graphs are the acquired raw signals of the EFPI sensor and the larger graphs are their FFT results. As shown in these figures, we can find that the FOS successfully detected the vibrations of frequencies up to 2 kHz actuated by the piezo-ceramic actuator.

From the experimental results, it can be seen that the constructed system can be used to measure the strain, temperature, and vibration simultaneously using only one sensor. Also, the proposed method is more efficient than conventional measuring methods which use physically separate sensors for each parameter. This sensor system is well-suited to health monitoring of various engineering structures, such as aircrafts, satellites, and composite structures, because strain, temperature, and vibration measurement can be simultaneously achieved for both surface mounted and embedded applications due to the simple profile of the sensor.
5. Conclusions

We have demonstrated a novel approach for the simultaneous measurement of strain, temperature, and vibration for structural health monitoring. This technique combines both a FBG/EFPI hybrid sensor system, which included a WSFL as a broadband light source, and the EFPI sensor in the hybrid sensor operated by a laser diode, by using a wavelength division multiplexer. The FBG/EFPI sensor system was used to measure strain and temperature simultaneously and the EFPI sensor system was used to measure vibration. We performed the simultaneous measurement of thermal strain, temperature, and vibration of an aluminum beam placed in a thermal chamber using the constructed measuring system and validated the efficiency of the proposed measurement technique.
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