Simulation Studies of Spectral Subtraction Based Temperature Compensation of FBG Sensor for Structural Health Monitoring

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ABSTRACT

Fiber Bragg gratings (FBGs) are optical fiber based sensor that are widely used for structural health monitoring. However, the strain and temperature components of the measurement are coupled. This paper discusses a method to decouple the two parameters using spectral subtraction.

INTRODUCTION

Fiber Bragg gratings (FBGs) are widely used for structural health monitoring of buildings, bridges, dams and other industrial structures [1]. The FBG is sensitive to both temperature (through coefficient of thermal expansion and thermo-optic coefficient) and strain (through strain optic coefficient). The development of proper solutions capable of decoupling temperature and strain responses of FBG sensors from each other has been one of the main challenges of the scientific community since the introduction of FBG sensors and is of vast scientific interest even now. In this paper, we endeavor to provide a more practical solution towards temperature compensation by using an FBG in combination with a thermocouple by adopting the spectral subtraction methodology.

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THEORY

In this section, we briefly describe the fundamental equations governing the FBG sensor, explain methodologies adopted in literature to decouple the strain and temperature sensitivity, and finally, the concept of the spectral subtraction. An FBG sensor consists of periodic modulation of refractive index in the fiber such that the counter-propagating modes are coupled. The Bragg wavelength is given by [2]

$$\lambda_B = 2n\Lambda \tag{1}$$

where n is the effective refractive index of the fiber core, and Λ is the period of fiber Bragg grating. The effect of temperature and strain on the change in the Bragg wavelength is given by

$$\Delta\lambda_B = \lambda_{B,o}\left(K_\varepsilon \Delta\varepsilon + K_T \Delta T\right) \tag{2}$$

The temperature compensation can be achieved if Eq. 2 is manipulated to eliminate one of the constants. This can be realized in the following ways. Consider the case, where $K_\varepsilon = 0$ or $K_T = 0$. If in Eq. 2, the temperature sensitivity can be made zero, the equation is then only dependent on the strain. Usually, this is achieved by enclosing the FBG in a glass tube. The strain sensitivity component can be made zero by enclosing the fiber in a metal tube and leaving the fiber ends free to move. Alternative to the above methodology, Eq. 2 can also be solved by setting up two equations to calculate the two variables, namely, K_ε and K_T. The best demonstration of this method was described in [3] where M.G.Xu et al., used superimposed FBGs and in [4] where two different FBGs were used. Each of the two FBGs has its own temperature and strain coefficients represented by subscripts 1 and 2. Eq. 2 thus could be rewritten as

$$\begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} = \begin{bmatrix} \lambda_{B,o} & 0 \\ 0 & \lambda_{B,o} \end{bmatrix} \begin{bmatrix} K_{\varepsilon 1} & K_{T1} \\ K_{\varepsilon 2} & K_{T2} \end{bmatrix} \tag{3}$$

In literature, the above equations have been implemented and solved by using two independent FBGs, or one FBG and one long period grating, or two FBGs arising out of a single FBG written on a single polarizing maintaining fiber. Other methodologies using encapsulated FBGs, or using FBGs welded to bimetals have been also tried in literature with varying success [5-7].

In the following, we describe the spectral subtraction method which is core to the approach of decoupling methodology adopted in this paper. Spectral subtraction is a widely used methodology for reducing noise in signals, and especially useful in audio processing [8]. The process is described below. Consider a noisy signal $y(t)$ consisting of noise free signal $x(t)$ and the noise $n(t)$ in time domain

$$y(t) = x(t) + n(t) \tag{4}$$

Converting the signal to frequency domain, one can obtain

$$Y(\omega) = X(\omega) + N(\omega) \tag{5}$$

Assume that we subtract only the magnitude part of the FFT $|N(\omega)|$ and retain the phase of the signal $Y(\omega)$. The $|N(\omega)|$ is also known as the estimation of the noise. The noise free signal is obtained by

$$X(\omega) = Y(\omega) - |N(\omega)| \tag{6}$$

In audio processing, the noise estimation could be made by measuring the noise without the actual signal. In our temperature and strain decoupling approach, the strain can be treated as signal of interest while the temperature as noise.

SIMULATION

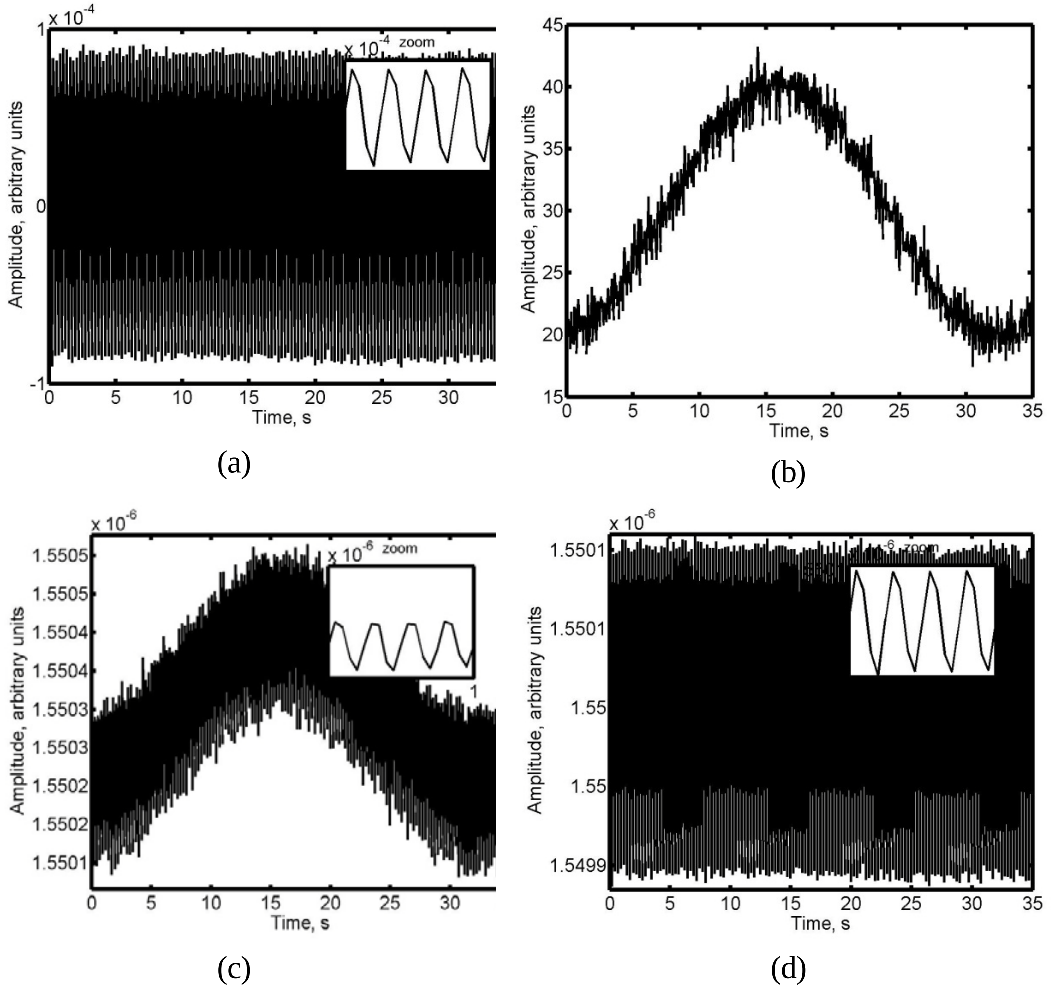
Here, the application of spectral subtraction for different temperature variation is presented. The strain is assumed to vary as sinusoid while the temperature is considered to have sinusoid, ramp, and square wave forms. We demonstrate that the frequency components arising out of the different variation patterns of temperature can be filtered in the frequency domain using spectral subtraction. We explain spectral subtraction methodology for the sinusoid variation in detail, and to avoid the redundancy, the procedure for the ramp and square wave forms is not explained in detail since it is similar to the one discussed for sinusoid variation.

Sine Wave Form: Eq.2 describes the change in wavelength shift as a function of temperature and strain. Generally, the strain sensitivity of an FBG sensor $K_\varepsilon = 1.2\,pm/\mu\varepsilon$ while the temperature sensitivity $K_T = 10\,pm/{}^oC$. The temperature varies as a sinusoid from 18 °C to 42 °C with the frequency of $f_T = 0.03\,Hz.$ as given in Eq.7, and is represented in Fig.1a. The strain varies as a sinusoid from +9 $\mu\varepsilon$ to -9 $\mu\varepsilon$ with the frequency of $f_\varepsilon = 4\,Hz.$ as shown in Eq.8 and in Fig.1b. The positive and negative values indicate the tension and the compression, respectively and thus, the periodic variation corresponds to periodic tension and compression.

$$T = A_1 \sin\left(2\pi f_\varepsilon t\right) + B_1 \sin\left(2\pi f_T t\right) + rn \qquad 7$$

$$\varepsilon = A_2 \sin\left(2\pi f_\varepsilon t\right) + B_2 \sin\left(2\pi f_T t\right) + rn \qquad 8$$

where rn is the random noise. In real life situation, sometimes, temperature modulation leads to strain modulation. Therefore, we have added a 1% of the strain to vary the signal at the same frequency as the temperature. Due to the autogenous heating, the temperature can vary with the same frequency as the strain modulation. Hence, we have added 10% of the temperature amplitude to vary at the frequency of the strain. These additions demonstrate the robustness of the simulation. The FBG signal is the additive of Eq. 7 and Eq. 8 as seen in Eq. 2 and as represented in Fig.1c. The frequency domain based spectral methodology for decoupling strain and temperature components is described below.

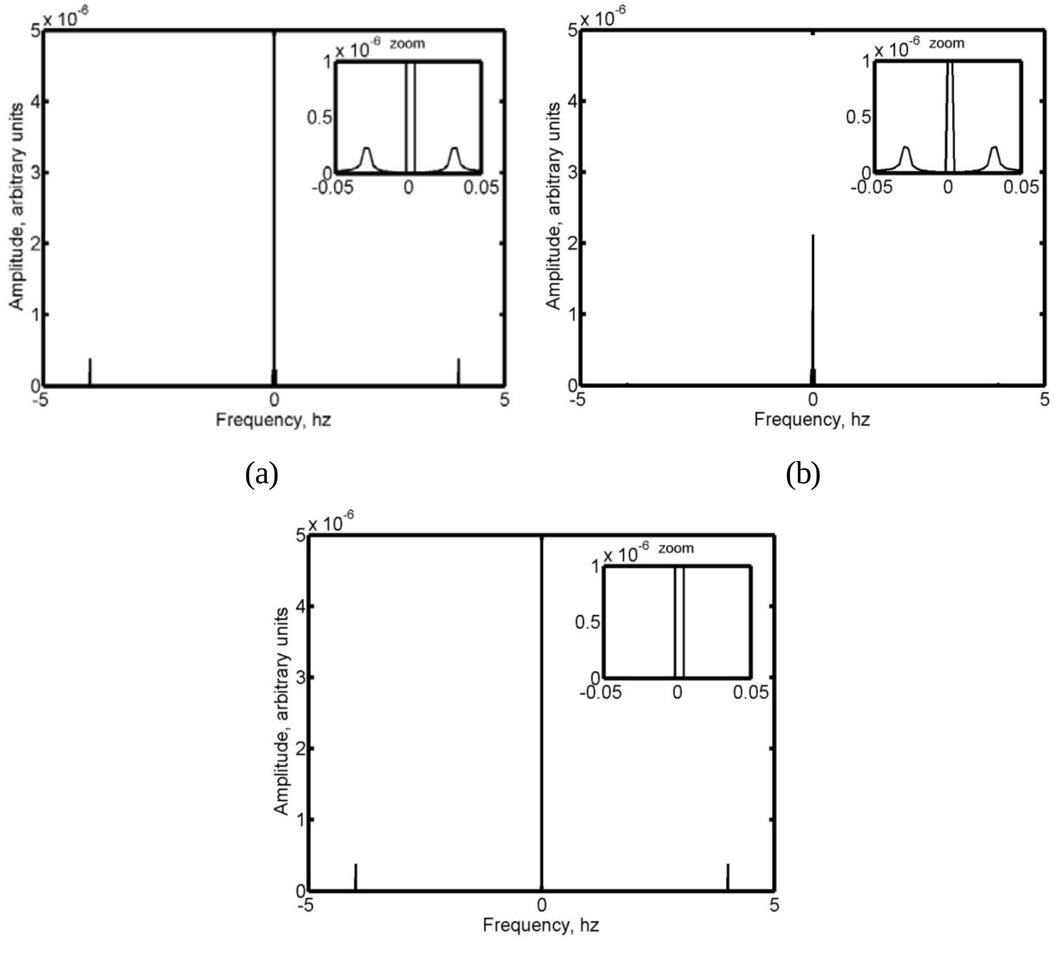


(a) (b)

(c) (d)

Figure 1 : A simulation test for spectral subtraction where in (a) the strain varies as a sinusoid (high frequency), (b) the temperature varies as a sinusoid (low frequency), (c) the high frequency strain is modulated by the low frequency temperature, and (d) the strain measurement is reconstructed.

1. The FBG signal is converted to frequency domain. The FFT of the FBG signal is shown in Fig.2a. It consists of both 4Hz strain signal and 0.03Hz temperature signal.
2. The temperature is converted to wavelength using the temperature sensitivity.
3. The temperature calculated in step 2 is converted into frequency domain. The FFT of the temperature signal is shown in Fig.2b. The signal consists of strong 0.03 Hz temperature signal, and also a weak 4Hz signal.
4. In the frequency domain, the temperature signal is subtracted from the FBG signal, Fig.2c. It could clearly be seen that the 0.03 Hz signal is no longer present in the frequency domain.
5. The temperature independent signal is obtained by obtaining the inverse FFT of the subtracted signal, Fig.1d.



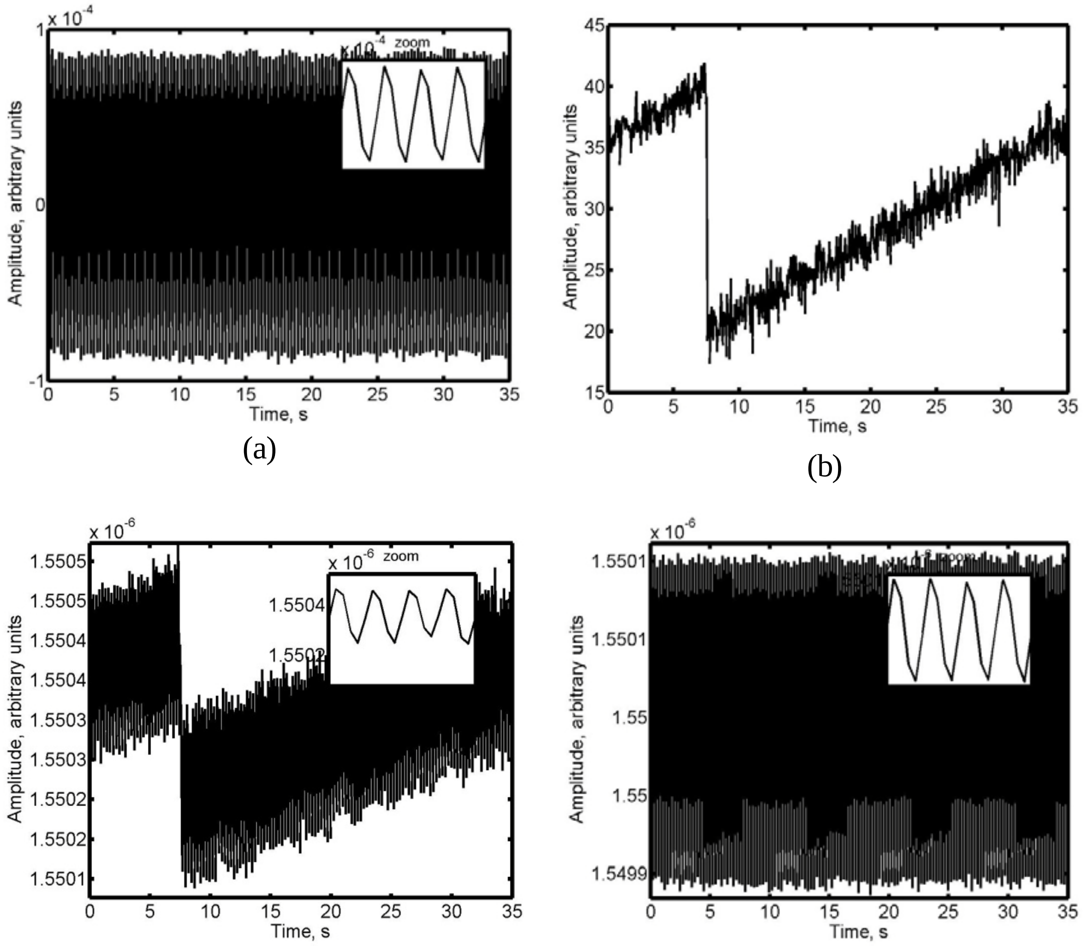
(a)

(b)

(c)

Figure 2: Spectral subtraction in the frequency domain: (a) the FFT of the FBG data, (b) the FFT of the temperature data, and (c) the subtraction of the FFT of the FBG and the temperature data.

Ramp Wave Form: While strain is varied as a sinusoid in cyclic fatigue tests, in most real life cases, temperature does not vary as a sinusoid. One common exception is the diurnal variation of temperature. However, in experiments, the temperature often varies linearly with time, which either increases or decreases, and therefore can be represented as ramp. It can be seen from Fig.3 that the temperature compensation can be achieved in the same way as in the case of sine variation.

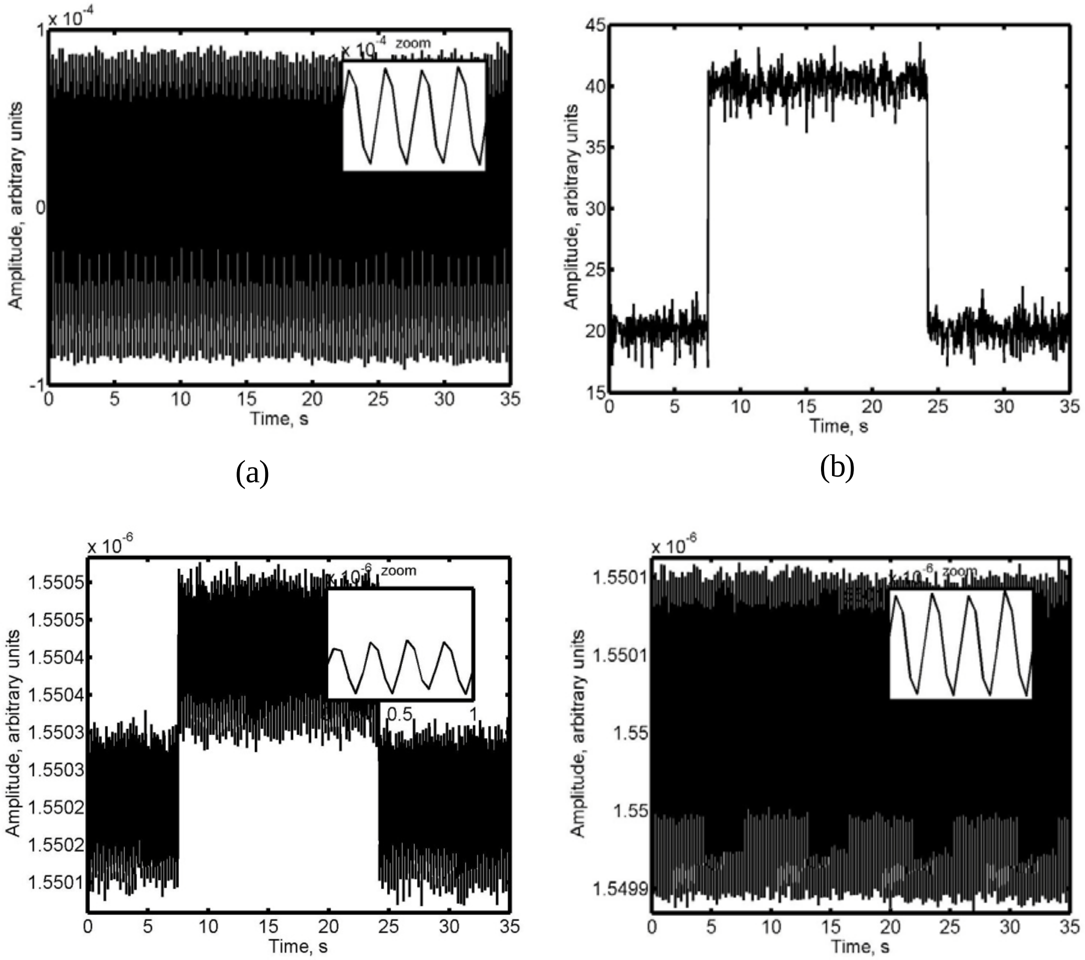


(a) (b)

(c) (d)

Figure 3: A simulation test for spectral subtraction where in (a) the strain varies as a sinusoid high frequency), (b) the temperature varies as a ramp (low frequency), (c) the high frequency strain is modulated by the low frequency temperature, and (d) the strain measurement is reconstructed.

Square Wave Form: It is possible in real life studies that there is a sudden increase or decrease in temperature and the temperature remains constant at this new higher or lower temperature. This could be represented as a square wave. In Fig.4, we find that this could also be eliminated in the frequency domain. The random variation in temperature has been included in all the three variation patterns of temperature. Thus we can say that the temperature can be compensated in FBG sensors if we know the temperature pattern using any temperature sensor.



(a) (b)

(c) (d)

Figure 4: A simulation test for spectral subtraction where in (a) the strain varies as a sinusoid (high frequency), (b) the temperature varies as a square (low frequency), (c) the high frequency strain is modulated by the low frequency temperature, and (d) the strain measurement is reconstructed.

CONCLUSION

In structural health monitoring using FBG sensors, the temperature and strain variations have to be decoupled for successful and true monitoring of the strain field. In this work, we have successfully demonstrated that the spectral subtraction method can be used to achieve this objective. The advantage of this method over the others described in literature is that only the pattern of temperature variation has to be monitored as against the magnitude of variation which is required by other methods. This approach also leads to reduction in error which will be demonstrated in our future publications.

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