Stabilized Interrogation and Multiplexing Techniques for Fiber Bragg Grating Vibration Sensors

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Abstract

We demonstrated a simple interrogation system for multiplexed fiber Bragg grating sensors with high frequency range. A tunable Fabry-Perot filter with narrow free spectral range (FSR) was used to simplify the multiplexing demodulator for FBG vibration sensors. A stabilization controlling unit was also developed for the maintenance of maximum sensitivity of the sensors. In order to verify the performance of the stabilization control unit, we measured the sensitivity of the FBG sensor by changing a environmental temperature, and the system showed an average sensitivity of 2.5 $n\varepsilon_{RMS}/\sqrt{Hz}$ for a stabilization controlled case. Finally, multi-points vibration tests using in-line FBG sensors were conducted to validate the multiplexing performance of the FBG system.

Keywords: Fiber optic sensor, Fiber Bragg grating, Stabilization control, Multiplexing, Vibration.

1. Introduction

Fiber Bragg grating (FBG) sensors have shown potential in real-time health monitoring systems because of strengths such as facility of multiplexing, immunity to electro-magnetic interference (EMI), small dimensions, etc. [1]. In the early development stage, FBG sensors were mainly applied to usage monitoring such as strain and temperature sensing, but the application fields are currently expanding to damage detection, such as impact and fracture monitoring [2,3].

In an FBG sensor, to detect acoustic emission (AE) signals from structural damage, an interrogation method of high frequency sensing must be used. While a scanning filter is widely used for the multiplexing demodulator in an FBG sensor system [4], in this case scanning frequency restricts the frequency range of the sensors. In general, most high frequency FBG systems have low multiplexing capability, and conversely, most multiplexed FBG systems have low frequency ranges [5].

Another issue to be addressed is the sensitivity fadeout problem in the intensity demodulation method, which is generally used in FBG vibration sensor systems. The physical properties of optical components, such as the Fabry-Perot filter, are easily influenced by external perturbations such as temperature change; therefore, it is difficult to maintain uniform sensitivity of the FBG sensors under changing environments. To avoid sensitivity fadeout problems some passive supplementary devices have been introduced. Multiple demodulators of 1/4 phase shifted [6] and passive temperature compensator in a tunable laser [7] have been employed in these devices. However, these passively controlled systems are simple only for a single head FBG sensor system and do not guarantee uniform sensitivity of a FBG vibration sensor.

In this paper, we present a novel stabilized FBG vibration sensor system with high frequency range. A stabilization controlling system was developed for maintenance of the maximum sensitivity of sensors. A tunable Fabry-Perot filter with narrow free spectral range (FSR) was used to simplify the multiplexing demodulator for FBG vibration sensors. We measured the sensitivity of the FBG vibrating sensor placed in a thermal chamber using the constructed FBG system, and conducted multi-points vibration tests to validate the multiplexing performance of the in-line FBG sensors.

2. FBG sensor system

2.1. Theory of measurement

A fiber Bragg grating is a periodic perturbation of a refractive index formed in the core of an optical fiber by using an intensive UV laser. If broadband light is emitted to a Bragg grating, grating only reflects the specific wavelength component and works like a narrowband reflecting filter [1], which is described by the Bragg condition in Equation (1):

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

where λ_B is the Bragg wavelength of FBG, n_e is the effective index of the fiber core, and Λ is the grating period. Because the effective index and grating period are functions of temperature and strain, the Bragg wavelength is changed when the temperature changes or mechanical strain is applied to the FBG sensor.

Figure 1 shows the concept of the demodulation method used in the FBG vibration sensor system. As shown in the figure, placing the narrow band filter at the operation point of the FBG spectrum, the output intensity from the filter changes when the Bragg wavelength shifts due to external perturbations. If we assume that the Bragg wavelength changes linearly as the applied strain and the slope of the FBG spectrum near the operation point are constant, the output intensity of the filter can be expressed as Equation (2) [7]:

$$I_{out} = I_{in}\left(T_0 + S\zeta_F\right) \tag{2}$$

where ζ_F is instantaneous strain applied to the FBG, and T_0 and S are the initial transmittance and slope at the operation point, respectively. From the above equation, within the linear region of the FBG spectrum strain, perturbations such as AE signals are displayed as the intensity variations of the output light.

2.2. Stabilization controlling unit

Both temperature and quasi-static strain can influence the optical properties of the Fabry-Perot filter and laser. As shown in Figure 1, if the filter wavelength moves from point A to point B of the FBG spectrum, the intensity of the output signal becomes smaller for the same input. This is called a fade-out problem, and it results in a sharp decrease in the sensitivity of the FBG vibration sensors.

Thus, in order to maintain maximum sensitivity of the FBG vibration sensors, the filtering wavelength of the demodulator should be fixed to the operation point of the FBG spectrum where the slope is the steepest. In this study, controlling the filtering position using a closed loop controller with a tunable Fabry-Perot filter (FFP-TF, Micron Optics, USA), we fixed the wavelength of the demodulator at the operation point, the most sensitive region of the FBG spectrum. The active control system used for the sensitivity stabilization consists of a tunable Fabry-Perot filter, a wavelength division multiplexer (WDM), and an I/O board (PCI-6110E, National Instruments, USA). Figure 2 shows a schematic diagram of the FBG vibration sensor system equipped with the stabilization controlling unit. Sensor signals are divided by the WDM and fed into the I/O board of the signal-processing computer through the photo detector. In the signal processor, the intensity level of the input signal is compared with that of the reference value in a comparator after low pass filtering. The difference between them is compensated through the wavelength shift of demodulating filter. Consequently, these continuous processes form a closed loop circuit, as shown in the dotted box in Figure 2.

If the signal processor has sufficient calculation speed to compensate for the wavelength shifts due to unexpected perturbations, the sensitivity of the FBG sensors are maintained regardless of the environmental influences. Thus, low frequency fluctuations such as thermal expansion are removed from the original signal and high frequency components of stress waves are separated and acquired. In this study, a PC based signal processing system was developed, wherein a GUI interface is employed and flexibility of future expansion to multi-channel FBG sensor systems is considered.

2.3. Multiplexing method

Because the Fabry-Perot demodulator for the FBG sensors is a multi-beam interferometer having a mirror cavity, the transmittance of the output beam can be expressed by the following equation [1]:

$$\frac{I_t}{I_i} = \frac{1}{1 + \left(\frac{2F}{\pi} \sin \frac{2\pi nd}{\lambda} \right)^2} \tag{3}$$

where I_i and I_t are the intensities of the input and output lights of the Fabry-Perot demodulator, respectively, F is the finesse, n is the refractive index, and d is the length of the Fabry-Perot cavity. Equation (3) is a periodic function and has maximum values when $\sin(2\pi nd/\lambda)$ becomes zero. Thus, the filtering wavelength of the Fabry-Perot demodulator has a regular wavelength interval, FSR (free spectral range), as given by

Equation (4) [1]:

$$\Delta\lambda = \frac{\lambda^2}{2nd} \tag{4}$$

Because a FBG sensor only reflects the Bragg wavelength of confined bandwidth, if we use FBG sensors with different reflecting wavelengths, we can detect the distributed physical properties using the multi-point sensing ability of an in-line FBG sensor array. Matching the Bragg wavelength to the filtering wavelength of the Fabry-Perot demodulator with a narrow FSR, plural FBG sensors can be simultaneously demodulated using a single demodulator. This demodulation scheme is equivalent to the employment of several filters with the same number of FBG sensors, thereby providing multiplexing ability with a high frequency range. By using the Fabry-Perot filter with a narrow FSR, the demodulation system can be downsized and simplified for cases that demand multiplexing as well as the ability to sense high frequency signals.

3. Experiment of stabilization controlled sensitivity measurement

3.1. Experimental apparatus and method

In this experiment, performance of the sensitivity control unit was tested by measuring the sensitivity of FBG vibration sensors in a thermal chamber. Sensitivity of the FBG sensors was measured from the noise level calculated from the power spectral density (PSD) diagram of a specific oscillation frequency [8].

The experimental apparatus is shown in Figure 3. A FBG sensor was bonded on the top surface of a PZT actuator (C-82, Fuji Ceramics corp., Japan), and an electric strain gage (ESG) was attached beside the FBG in order to measure the applied strain as a reference value. The PZT actuator was simply supported by silicon rubbers at two ends and placed in a thermal chamber. Sensitivity of the FBG sensor was measured by changing the temperature of the thermal chamber at 2 ºC intervals, and the change of sensitivities was compared between the stability controlled case and uncontrolled case. Temperature was raised to an initial state of 36 ºC and naturally cooled to 30 ºC in the thermal chamber.

Strain signals of the FBG sensor were converted from the intensity of the photo detector by using the reference strain value measured by the ESG at the applied voltage of the PZT, and these output signals were used to calculate the sensitivity of the FBG sensor. The amplitude of the input voltage from the digital function generator (AFG320, Tektronix, Japan) was set to change from –10 *V* to 10 *V*, and the oscillation frequency was 1 *kHz*.

3.2. Experimental results and discussions

Figure 4 shows the intensity variation of FBG output signals by the temperature change in the thermal chamber without controlling sensitivity stabilization. At 36 ºC when the filtering wavelength of the F-P demodulator was set to the operation point of the FBG spectrum, the amplitude of the FBG output was measured as –40 ~ 40 *mV*. As the temperature was decreased, however, the amplitude of the FBG signal decreased, because the filtering wavelength moved to a lower slope position of the FBG specturm without stabilization control.

Figure 5 provides a comparison of sensitivity and signal to noise ratio (SNR) measurement of the FBG vibration sensor system between the results obtained for the stabilization controlled case and uncontrolled case. In the uncontrolled case, Figure 5(a), SNR was measured to 52.70 *dB* at the reference temperature and reduced to 34.70 *dB* as the temperature decreased by 6 degrees. The slope of the SNR plot steeply decreased as the temperature difference increased from the reference condition; therefore, the sensitivity representing the noise level of the output signal of the FBG became poorer as the environmental temperature changed.

On the contrary, we could maintain SNR and sensitivity of 52.43 *dB* and 2.46 $n\varepsilon_{RMS}/\sqrt{Hz}$, respectively, in the stabilization controlled case, because the filtering wavelength of the F-P demodulator was continuously controlled so as to be tuned to the operation point of the FBG spectrum. Comparing Figure 5(a) and Figure 5(b), deviation of the measurement in the stabilization controlled case is observed to be smaller than that of the uncontrolled case except for the result of the reference condition. From these results, we can confirm that environmental changes applied to both optical components comprising the FBG system and FBG sensors in the thermal chamber influence the sensitivity of the FBG vibration sensor, and the applied stabilization controlled FBG system successfully compensated sensitivity decline factors such as temperature change.

Figure 6 provides a comparison of the spectrums of the tunable F-P demodulator between the stabilization controlled case and uncontrolled case. For the stabilization uncontrolled case, although the center wavelength of the FBG was shifted by external temperature change, the filtering wavelength of the demodulator did not move together with Bragg wavelength; therefore, the intensity of the filtered output was reduced, as shown in Figure 6(a). This intensity variation induces a sensitivity change of the FBG sensors and can also cause intensity drift of the FBG output signal with no relation to vibration input signals. As shown in Figure 6(b), in the stabilization controlled case, the filtering wavelength of the F-P demodulator was simultaneously shifted according to the FBG shift amount, and consequently we could maintain the most sensitive condition of the FBG vibration sensor system.

4. Experiment of multiplexed vibration measurement

4.1. Experimental apparatus and method

We performed multiplexed vibration tests of two in-line FBG sensors to verify whether the proposed multiplexing demodulator could extract two different input signals simultaneously.

Figure 7 shows the spectrum of the two FBG sensors and the tunable F-P demodulator used for the vibration tests. FSR of the F-P filter was 23.8 *nm*, and the filter could simultaneously demodulate two FBG sensors from a wavelength of 1530 *nm* to 1560 *nm*. The two FBG sensors have center wavelengths of 1532.44*nm* and 1556.26 *nm*, respectively, and the wavelength interval between the two FBGs was designed to fit the FSR of the F-P demodulator.

Two specimens used for the experiment were made of aluminum beam and fixed to jigs to make cantilevers. The shape of the specimen is presented in Figure 8. Two FBG sensors in one sensing line were bonded to the upper surface of the two cantilever beam specimens, respectively, and PZT actuators (C82, Fuji Ceramics corp., Japan) were attached on the bottom side of the specimens. A schematic diagram of the experimental apparatus is shown in Figure 9. The two channel output signals of the digital function generator (AFG320, Tektronix, Japan) were amplified and vibrated the PZT actuators, PZT1 and PZT2, on Specimen1 and Specimen2, with different oscillation frequencies. In the first test, two cantilevers were vibrated at 200 *Hz* and 400 *Hz*, respectively, and in the second test, the oscillating frequencies were raised to 50 *kHz* and 100 *kHz*. The amplitude of the applied vibration was restricted within 50 $\mu\varepsilon$, which is the linear strain range determined by the operation range of the FBG spectrum.

The oscillating frequencies are selected to assess whether the multiplexed FBG sensor system can detect the vibration signals with the frequency range of structural fracture signals.

4.2. Experimental results and discussions

Experimental results of the multiplexed vibration tests are shown in Figures 10 to 11. In the first experiment, FBG1 and FBG2 were oscillated with frequencies of 200 *Hz* and 400 *Hz*, repetitively. In Figure 10, although the amplitude of the applied vibration was small, two FBG sensors clearly detected the sinusoidal input signals in the audio frequency range. Comparing the power spectrums of the two outputs, FBG1 and FBG2, clear peaks of 200 *Hz* and 400 *Hz* can be observed in the spectrum domain; therefore, we confirmed that the F-P filter with narrow FSR can successfully demodulate two different input signals from two FBG sensors simultaneously without inducing any interference.

Figure 11 shows the results from the ultrasonic input signals. Two FBG sensors were simultaneously vibrated with frequencies of 50 *kHz* and 100 *kHz*, and these oscillating frequencies were in the range of the fracture signals of composite materials generally used in the smart structures. Like the preceding results, the two FBG signals were separated by the single F-P demodulator, and we could observe sharp peaks of the oscillation frequencies, 50 *kHz* and 100 *kHz*, in the power spectrums.

In conclusion, we have confirmed that the FBG interrogation system can demodulate two different input signals simultaneously up to the ultrasonic frequency range using a single F-P filter of narrow FSR.

5. Conclusions

We have demonstrated a novel approach for multiplexed FBG vibration sensors of high frequency range. This technique uses a tunable F-P filter with narrow free spectral range (FSR) as a multiplexing demodulator for two FBG vibration sensors, and the sensitivity of the sensors is maintained in a stable manner by controlling the tuning voltage of the F-P filter. We measured the sensitivity of the FBG vibration sensor in a thermal chamber to test the performance of the stabilization controlling unit, and performed multiplexed vibration tests of two in-line FBG sensors to confirm that the proposed demodulating method can extract the two high frequency input signals simultaneously.

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