Distributed Measurements with a Long Gauge FBG Sensor Using Optical Frequency Domain Reflectometry (1st Report, System Investigation Using Optical Simulation Model) *

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Abstract

Optical fiber sensors have many advantages for structural health monitoring and are often used to monitor the strain distribution of structures. However, using Fiber Bragg Grating (FBG) sensors with a general interrogation system, e.g. Wavelength Division Multiplexing (WDM), permits only the measurement of average strain within the gauge length and moreover, a large number of FBG sensors may be necessary to monitor overall stress concentrations. A distributed strain sensor with a higher spatial resolution and longer sensing length is therefore desired for the accurate and effective monitoring of stress concentration. To meet this need, we present a new strain measurement system with a long gauge FBG sensor based on the principle of Optical Frequency Domain Reflectometry (OFDR) which enables us to measure fully distributed strain at high spatial resolution. In this paper, we describe the principle and optical simulation model of our proposed measurement system and show the results of numerical calculations.

Key words: Optical Fiber Sensor, Measurement of Strain Distribution, FBG, OFDR, Health Monitoring, Smart Structure

1. Introduction

Recently, structural health monitoring (SHM) has been receiving attention as a means to secure the safety and reliability of a variety of mechanical structures. SHM can provide evaluation of the integrity of a structure and an estimate of its remaining life, optimization of maintenance, feedback to the design process from knowledge of the structure's state of operation and the actual operational loads it experiences, and thereby improve the structure's reliability. Moreover, if an accident that causes damage should occur, it is hoped that the knowledge of state of damage obtained by SHM can be used to prevent the damage from spreading. To be fully effective, a structural health monitoring sensor system must be durable, reliable, and established as a network over the whole structure.

In monitoring the behavior of an entire structure in actual operation, using general strain gauges and acceleration pickups can cause problems of handling and weight increase due to the large amount of wiring required. On the other hand, a single optical fiber sensor can make simultaneous measurements of a wide range of information⁽¹⁾ and because it has small diameter and low weight, some researchers have attempted to embed such sensors

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directly into fiber-reinforced composite structures⁽²⁾. Optical fiber sensors have further advantages such as immunity to electromagnetic noise, excellent durability and corrosion resistance. With these features, optical fiber sensors can address many of the problems in practical structural health monitoring and can be used to greatly improve the reliability of the entire structure.

Among optical fiber sensors, the Fiber Bragg Grating (FBG) sensor is gathering attention. An FBG sensor can accurately measure strain and temperature and has been used in various scenarios. FBG sensors with some interrogation systems are typically employed for quasi-distributed strain or temperature measurements in which two or more FBG sensors are allocated to one optical fiber. The Wavelength Division Multiplexing (WDM) method has been used widely for quasi-distributed measurement, and with WDM, a wavelength band must be allocated for each sensor. However, in recent years the Optical Frequency Domain Reflectometry (OFDR) method has attracted more attention⁽³⁾ than WDM because it can be multiplexed over ten times or more the number of FBG sensors as WDM⁽⁴⁾⁽⁵⁾. Both of these methods use FBG sensors of about 5 to 25 mm in length, and can measure the average strain and temperature generated at the discrete parts of the gauge where the FBG sensors are located. However, it is difficult for these methods to observe directly the stress concentrations and fatigue cracks which cause the destruction of a structure as strain distribution.

In this research, we show that fully distributed strain and temperature measurements with high spatial resolution can be implemented using optical frequency domain reflectometry (OFDR) with long gauge FBGs⁽⁶⁾⁽⁷⁾. Brillouin Optical Time Domain Reflectometry (BOTDR)⁽⁸⁾ and Brillouin Optical Correlation Domain Analysis (BOCDA)⁽⁹⁾ are well-known distributed measurement technologies with spatial resolutions of about 1 m and 1 cm respectively. The measurement technique presented in this research has a high spatial resolution of less than 1 mm. In order to systematize distributed measurement with long gauge FBGs using OFDR and to formulate a basis for system design, we construct an optical simulation model and examine the influences of the component parameters of the measurement system on the measurement results. Although this report mainly discusses strain measurement, the measurement technique can also be applied to the measurement of temperature and various other physical quantities by using appropriate transducers.

2. Outline of strain distributed measurement using OFDR

This section describes the principle of the FBG sensor used for strain measurement and explains the outline of the distributed strain measurement technique with a long gauge FBG sensor using OFDR proposed in this research.

2.1 FBG sensor

An FBG is a periodic perturbation of the refractive index in the core of an optical fiber, and is used as an optical fiber type device that functions as an optical filter in telecommunications. Because the diffraction grating can be formed nondestructively within the optical fiber, the FBG has many advantages: low loss, small size, high reliability and uses the same medium as the transmission optical fiber.

As shown in Fig. 1, the basic principle of operation commonly used in FBG-based sensor systems is to monitor the shift of the center wavelength in the returned spectrum due to changes in strain or temperature. The center wavelength is called Bragg wavelength, λ_B and is given as

$$\lambda_B = 2n\Lambda \quad (1)$$

where Λ is the grating pitch and n is the effective refractive index of the core. When a spectrally broadband source of light is injected into a fiber with an FBG, a narrowband

Fig.1 Fiber Bragg Grating sensor

Fig.2 Principle of OFDR sensor

spectral component at the Bragg wavelength is reflected by the grating. In order to measure the strain of a structural member using an FBG sensor, the sensor is usually bonded on its surface. As the strain changes the periodic pitch Λ , we observe a shift of the center wavelength. The gauge length of an FBG sensor is typically from 3 to 25 mm, so it is as large as a conventional strain gauge. A typical FBG can measure average strain or temperature in the gauge.

In this research, the strain and the temperature distribution generated in the FBG are measured by using OFDR and a new data analysis method, and the optical reflection characteristic is obtained at arbitrary positions within an FBG more than 100 mm in length.

2.2 Reflection characteristics of OFDR system

Figure 2 shows the conceptual diagram of an optical system for distributed strain measurement with OFDR. The system consists of a wavelength tunable laser, a photodiode detector, a broadband reflector, and an FBG sensor. The broadband reflector and FBG sensor compose an interferometer. The wavelength of the wavelength tunable laser is continuously changed, and the strength of the reflected light at each wavelength is measured by the photodiode detector.

Each minute section of the FBG strongly reflects only light of a certain wavelength, and the relationship between the wave number k of the light and the reflected light strength becomes as shown in the lower right of Fig. 2. The wave number k in which the peak is shown depends on the strain at the FBG. Here, the relation between the wave number k and the wavelength λ is expressed as

$$k = 2\pi/\lambda \quad (2)$$

The formulation in this paper is described by the wave number of light, and results of the measurement and analysis are shown in terms of the wavelength of light.

Light reflected from a minute section of the FBG and light reflected from the broadband reflector have an optical path difference of $2nL_i$. These two reflected light components make the interferometer as described in detail in section 3. The AC component of the light intensity in the interferometer varies as a cosine function of the wave number k , and is given by

$$\tilde{D}_{ITF} = A \cos(2nL_i k) \quad (3)$$

where n is the effective refractive index of the optical fiber core.

By the two above-mentioned actions, the light intensity detected by the photodiode detector changes with the cycle and the peak for wave number k as shown in the lower left of Fig. 2. It is finally written as

$$\tilde{D}_{DTC} = R_{FBG}(k) \cos(2nL_i k) \quad (4)$$

where $R_{FBG}(k)$ is a function of the wave number (or the wavelength) and shows the reflection property in a minute section of the FBG. The position of the minute section within the FBG can be determined by the frequency of this signal observed by the photodiode

detector, and the strain can be determined by the wave number k at which the peak power is obtained.

Here, we discuss the reflection from a minute section within the FBG. For the all parts of the FBG, the light intensity signal is observed as a summation of signals of different frequencies that correspond to the optical path difference L_i .

2.3 Data analysis method

As mentioned above, when the wavelength of the tunable laser is changed continuously, the signal observed by the photodiode detector becomes the summation of signals of different frequencies that correspond to different positions within the FBG. Analysis by STFT (Short Time Fourier Transform) provides the spectrum at each position. By applying an appropriate window for a particular wavelength, the signal around the wavelength focused on is extracted. When the extracted signal is analyzed by Fast Fourier transform, the power of each frequency component in the signal is obtained. By applying Fourier transform analysis with a sliding window to all wavelength zones, we can obtain a spectrogram in which the x-axis shows wavelength, the y-axis shows the optical path distance and the color shows the power of the signal. For each optical wavelength, this spectrogram shows the reflection strength at arbitrary positions within the FBG.

A measurement test was carried out to validate this method as follows. An FBG of 100 mm length was bonded on the center section of the test specimen shown in Fig. 3 and a tensile test was conducted. Four strain gauges were placed at P1–P4 of Fig. 3 as a reference. The test specimen was cut in a dumbbell shape, giving a non-uniform strain distribution. Figure 4 shows the spectrogram analytical result when the tensile loading non-acts and acts respectively. The x-axis shows optical wavelength and the y-axis shows position. The size of the power output is displayed by color density. In this test, the reflected light strength is sampled by wave number 0.14 1/m spacing. This gives a 0.053 pm wavelength spacing at a wavelength of 1544 nm, although the sampling wavelength spacing changes according to the measured wavelength region because the wave number and the wavelength are related by Eq. (2). Since the FBG is located at 3.3 m, the cosine function element of Eq. (4) has a cycle of wave number 0.66 1/m corresponding to a wavelength of 0.25 pm. The half-value width of the intensity spectrum of reflected light is about 100 pm. In the spectrogram

Fig.3 Specimen of distributed measurement with a 100mm FBG

Fig.4 Spectrogram of test measurement

Fig.5 Measurement of strain distribution with OFDR

analysis, a Hanning window of 4,000 points length corresponding to a wavelength width of about 210 pm is used, and FFT is applied to $16,384 (=2^{14})$ points of data, including zero-value data, in order to obtain high spatial resolution. The scroll amount of the window is 20 points. As a result, the spectrogram is obtained at each 1.1 pm wavelength and each 0.94 mm distance interval. The window length influences both the distance resolution and the wavelength resolution, and it is necessary to trade off between the two. Here, we select the minimum window length that shows the strain distribution accurately. In the present paper, the spectrogram analysis uses these parameters unless otherwise stated.

The spectrograms in Fig. 4 provide the wavelength at which the reflected light strength at an arbitrary point within the 100 mm -long FBG gives the maximum value. Comparing the two graphs, the spectrum peak is shifted to the right when the specimen is loaded. This shows that strain on FBG increases the wavelength of the reflected light and the amount of shift of the optical wavelength corresponds to the strain value. The amount of shift of this reflected light wavelength is converted into strain, and Fig. 5 shows the result of strain at arbitrary points in the FBG. The zero on the x -axis shows the center of FBG, the circles show measurement results by the four strain gauges, the dashed lines show the results of analysis by the finite element method, and the solid lines show the results of measurement by our proposed system. It can be seen that our proposed measurement system is able to measure the strain distribution of the test specimen and that the strain distribution measurement result varies linearly with load. This validates the effectiveness of our measurement system.

There is some disturbance in the strain measurement results at around -20 , $+5$ and $+25\text{ mm}$ in Fig. 5. These regions correspond to 3.285 , 3.310 , 3.330 m in the spectrogram analysis results, at which wavelengths the strength of the reflected light becomes very low, and so the peak wavelength shifts could not be measured accurately.

The 100 mm FBG in our experiment was fabricated with the mask for a 25 mm apodized FBG. In an apodized FBG, the strength of the reflection becomes weaker at both ends, and so we observe a drop in the reflected light strength at the edges of the 25 mm FBG mask. In other words, our proposed system can observe non-uniformity of the FBG and could be used for quality assessment in the FBG manufacturing process.

3. Construction and verification of simulation model

This section outlines our proposed measurement system and describes its optical simulation modeling based on theoretical formulae. The model's validity is verified by comparing the simulation result with the experimental result.

3.1 Outline of the measurement system

Figure 6 shows the composition of our measurement system. The system consists of a wavelength tunable laser (Ando Electric Co. AQ4321A), two photodiode detectors (D1, D2), three broadband reflectors (R1, R2, R3), three 3dB couplers (C1, C2, C3), a long gauge FBG and a desktop computer with an A/D converter (National Instruments PCI-6115).

Light from the wavelength tunable laser is split into two beams by the 3dB coupler C1. One beam reaches the interferometer composed of D1, C2, R1 and R2. This beam can be reflected by two broadband reflectors R1, R2, and the interference optical power is measured by photodiode detector D1. In the same way, the interference optical power with the interferometer composed of D2, C3, R3 and the FBG is measured by photodiode detector D2.

The photodiode detector signals are sampled by the A/D converter and acquired as voltage signals by the computer. The signal measured by photodiode detector D1 is a sine

Fig.6 Measurement system with OFDR

function that varies by the constant wave number interval. Therefore, when a certain output value is set as a trigger threshold, the optical power signal can be detected with photodiode detector D2 in the constant wave number interval. By applying the data analysis method described in the above section to this signal, the reflection property within the FBG can be obtained.

3.2 Optical modeling of the OFDR measurement system

First, we model the interferometer composed of D1, C2, R1 and R2 in Fig. 6. Reflected light LR_{R1} and LR_{R2} from R1 and R2 are shown below respectively as functions of wave number k .

$$LR_{R1} = e^{i(2nL_{R1}k+\pi)} \quad (5)$$

$$LR_{R2} = e^{i(2nL_{R2}k+\pi)} \quad (6)$$

Here, n is the effective refractive index, L_{R1} is the distance between D1 and R1, and L_{R2} is the distance between D1 and R2. Eqs. (5) and (6) give the light intensity signal observed by D1 as follows:

$$\begin{aligned} D_1 &= (LR_{R1} + LR_{R2})(LR_{R1} + LR_{R2})^* \\ &= 2\{1 + \cos(2nL_R k)\} \end{aligned} \quad (7)$$

where $L_R = L_{R2} - L_{R1}$. As the laser is tuned, Eq. (7) implies that the light intensity observed by D1 varies cyclically depending on a wave number change Δk , given as

$$\Delta k = \frac{\pi}{nL_R} \quad (8)$$

The positive-going zero-crossing of the signal at D1 is used to trigger the sampling of the signal at D2.

Next, we model the interferometer composed of D2, C3, R3, and FBG. Similarly to Eq. (7), the light intensity signal observed by D2 is expressed as

$$D_2 = (LR_{R3} + LR_{FBG})(LR_{R3} + LR_{FBG})^* \quad (9)$$

where LR_{R3} and LR_{FBG} are light reflected from R3 and FBG, respectively. LR_{R3} is given by

$$LR_{R3} = e^{i(2nL_{R3}k+\pi)} \quad (10)$$

where L_{R3} is the distance between D2 and R3. LR_{FBG} can be determined by the transfer matrix method based on coupled mode theory⁽¹⁰⁾. First, we divide the grating with gauge length L into M uniform sections of length Δz as shown in Fig. 7. The input/output relationship for the interferometer system of Fig. 7 is given by

$$\begin{bmatrix} R_0 \\ S_0 \end{bmatrix} = T \begin{bmatrix} R_M \\ S_M \end{bmatrix}; \quad T = P_G \cdot F_1 \cdot F_2 \cdots F_i \cdots F_M \quad (11)$$

Fig.7 Model of interferometer with FBG

where R_0 and R_M are respectively the amplitudes of the forward propagating mode at the detector side end and at the another end. S_0 and S_M are respectively the amplitudes of the backward propagating mode at the detector side end and at the other end. The components of F_i and the phase-shift matrix, P_G , are given by

$$F_i = \begin{bmatrix} \cosh(\gamma_B \Delta z) - i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta z) & -i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) \\ i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) & \cosh(\gamma_B \Delta z) + i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta z) \end{bmatrix} \quad (12)$$

$$P_G = \begin{bmatrix} e^{-i \cdot n(L_{R3} + L_G)k} & 0 \\ 0 & e^{i \cdot n(L_{R3} + L_G)k} \end{bmatrix} \quad (13)$$

where γ_B , $\hat{\sigma}$ and κ are respectively the mode-coupling coefficient, the general “dc” self-coupling coefficient and the “ac” self-coupling coefficient. L_G is the distance between R3 and the detector side end in the FBG. Finally, when the boundary conditions ($R_0 = 1$ and $S_M = 0$) are applied to Eq. (11), we obtain

$$\begin{aligned} LR_{FBG} &= S_0 \\ &= \frac{T_{21}}{T_{11}} \end{aligned} \quad (14)$$

The D2 signal sampled at the constant wave number Δk can be calculated by Eqs. (11)–(14).

3.3 Verification of simulation model

We now verify the validity of the simulation model. First, we simulated the strain distribution along an FBG with a gauge length of 100 mm under a stress-free condition. The parameters used for the simulation are as follows.

Visibility :	$\nu = 0.3944$
Length of FBG :	$L = 100 \text{ mm}$
Effective refractive index :	$n_{eff} = 1.45$
Design wavelength :	$\lambda_D = 1548.16 \text{ nm}$
Averaged index change :	$\overline{\delta n_{eff}} = 3.10 \times 10^{-6}$
Position of FBG :	$L_G = 4.96 \text{ m}$

Figure 8 shows the D2 output signals obtained from the experiment and the simulation, with the two signals normalized by their maximum values. Then, Fig. 9 shows the spectrogram obtained by the above-mentioned data analysis method. In the experiment result of Fig. 8, we observe a weak signal at the left of the largest peak. The spectrogram of the experiment in Fig. 9 shows that the center wavelength of the FBG is not constant; in other words, the grating spacing in the FBG is not constant. The experimental result and the simulation are in very good agreement except for a fluctuation of the center wavelength that

Fig.8 Output signals of experiment and simulation

Fig.9 Spectrograms of experiment and simulation with a 100mm FBG

Fig.10 Output signal and spectrogram of simulation with a non-uniform 100mm FBG

appears in the experiment because the simulation assumes that the design center wavelength is constant within the FBG. However, because the FBG used in the experiment was fabricated with an apodize-free 100 mm mask, we observe a non-uniformity of reflection strength as seen in Fig. 4.

Figure 10 shows the simulation result for a 100 mm FBG in which the design center wavelength is shifted by 0.2 nm at its center. Two peaks appear in the output signal separated by 0.2 nm. The spectrogram can express the reflection center wavelength shifted at the FBG center position. The simulation model in this paper can be used not only for an FBG with a stepped center wavelength profile but also for the FBGs shown in Figs. 8 and 9 by using a finer center wavelength distribution.

Comparison of the simulation and experimental results demonstrates that the model simulates the optical properties of the 100 mm FBG used in the experiment very well and simulates the case that the center wavelength within the FBG is shifted by local strain. This validates the simulation model.

4. Parameter study of measurement system by simulation model

In this section, we investigate the influence of the window length on spatial resolution and examine the possible lengths of FBG that can be used with our proposed measurement system.

Fig.11 Spectrograms of a non-uniform 100mm FBG
(Window length = 4000,6000,8000)

Fig.12 Response distance of a non-uniform 100mm FBG
(Window length = 4000,6000,8000)

4.1 Influence of window length

To investigate the effect of varying window length, we simulated the strain distribution along a 100 mm FBG in which the design center wavelength is shifted by 1.2 nm at its center. Figure 11 shows the spectrograms obtained by a Hanning window with data lengths of 4,000, 6,000 and 8,000 respectively corresponding to wavelength widths of about 210 pm, 320 pm, and 420 pm. FFT was applied to 65,536 ($=2^{16}$) points of data including zero-value data. The scroll amount of the window was 20 points. As a result, spectrograms were obtained at each 1.1 pm wavelength and each 0.24 mm interval. In addition, the center wavelength of the spectrum was determined by calculating the center of the full width at half maximum (FWHM) at each position in the spectrogram. The center wavelength profiles of the FBG center section are shown in Fig. 12.

We define spatial resolution as the distance between the points at which the strain values reach 10% and 90% of the maximum strain. Figure 12 shows that the spatial resolutions of 1.6 mm, 1.1 mm and 0.6 mm were achieved with data length windows of 4,000, 6,000 and 8,000, respectively. This implies that spectrogram position resolution is improved by increasing the window length.

On the other hand, the spectrogram wavelength resolution decreases as the window length increases. In Fig. 11, it can be confirmed that spectrum width broadens in the wavelength direction as the window length is enlarged, and in this case it is feared that the center wavelength estimation accuracy decreases. The RMS values of the measurement error in the sections 2.000–2.048 m and 2.052–2.100 m that exclude the FBG center section were 0.28 pm, 0.30 pm and 0.27 pm for 4,000, 6,000 and 8,000 data length windows, respectively. As a result, it is found that the center wavelength calculated as the center of the full width at half maximum is not affected by increasing the window length.

4.2 2m length FBG

A 100 mm FBG was used in the analysis and experiment above, but a longer measurement range may be required to measure the strain distribution of a large-scale structure. In this section we present the simulation result for a 2,000 mm-long FBG.

Figure 13 shows the results of the simulation when the averaged index change was adjusted to 3.1×10^{-6} as well as the case of a 100 mm FBG, and the FBG was set at the

Fig.13 Spectrogram and Peak power of 2000mm FBG
(Averaged index change = 3.1×10^{-6})

Fig.14 Spectrogram and Peak power of 2000mm FBG
(Averaged index change = 1.03×10^{-6})

Fig.15 Spectrogram and Peak power of 2000mm FBG
(Averaged index change = 3.1×10^{-7})

Fig.16 Spectrogram and Peak power of 2000mm chirped FBG
(Averaged index change = 3.1×10^{-6})

position from 4 m to 6 m. The left graph in Fig. 13 shows the spectrogram analysis result and the right graph shows the maximum value of spectral power at each position. It was found that the reflected light strength peak is not constant at the position from 4 m to 6 m, differing from the 100 mm FBG. This implies that the incident light does not reach the end of the FBG. In addition, light reflected directly from the FBG and light which is reflected multiply within the FBG can work as interferometers whose optical path difference can take various values. It is thought that the signals with various optical path differences appear outside of the range from 4 m to 6 m where the FBG is located.

Next, simulation results for cases where the averaged index changes were adjusted to 1.03×10^{-6} (1/3 of the above case) and 3.1×10^{-7} (1/10 of the above case) are shown in Figs. 14 and 15 respectively. The smaller averaged index change gives a more constant reflected light strength in the section from 4 m to 6 m where the FBG exists. By adjusting the averaged index change to 3.1×10^{-7} , a 2,000 mm-long FBG can be used for measurement within the whole region where the FBG exists. Lowering the averaged index change of the FBG means lowering the reflectance per unit length of the FBG.

A chirped FBG can extend the measurement range as well as an FBG with low averaged index change. Figure 16 shows the simulation result for FBGs for which the averaged index change and chirp rate were adjusted to 3.1×10^{-6} (as well as Fig. 13) and 0.005 nm/mm respectively. Because the reflection center wavelength varies within the FBG, light attenuation within the FBG becomes small. Therefore, the reflected light strengths

from arbitrary positions within the FBG are constant, and the chirped FBG can be used for long measurement distances.

5. Conclusions

In this paper, we propose an OFDR-based distributed strain sensing system that can measure the strain distribution along a long gauge FBG with high spatial resolution. In addition, we constructed an optical simulation model for our measurement system, and examined the influences of the measuring system component parameters on the strain measurement. The results of measurement simulation and experiments prove that our method has a spatial resolution of less than 1 mm.

With the exception of the wavelength tunable laser, our measurement system is composed of such simple optical devices that it can be miniaturized and applied practical use in the near future. There are still some difficulties in manufacturing long gauge FBGs, but our proposed system could be applied to quality assessment in the manufacturing process. In future, we will use the simulation model to design a measurement system with higher performance.

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