Structural Health Monitoring Based on Strain Distributions Measured by Fiber-optic Sensors

Hideaki Murayama[1], **Daichi Wada**[1], **and Hirotaka Igawa**[2]

[1]School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[2]Japan Aerospace Exploration Agency
6-13-1 Ohsawa, Mitaka, Tokyo 181-0015, Japan

Abstract— We have developed a fiber-optic sensing technique that provides strain distributions along a sensing fiber with a high spatial resolution. Using long-length fiber Bragg gratings (FBGs), strain profile along FBGs is obtained based on optical frequency domain reflectometry. We demonstrate an experimental example of the technique and show its applicability for the purpose of structural health monitoring. We also demonstrate a simulation-based design process which has been developed in order to allow numerical discussion about the applicability and the capability of the sensing technique.

1. INTRODUCTION

The purpose of structural health monitoring (SHM) is to lead a structure such as aerospace, ship, and civil and mechanical engineering infrastructure, to be safer at the lower cost. SHM systems conduct assessment of structural integrity during manufacturing and/or in-service operation, which results in optimal operation, effective maintenance and longer service life [1].

Optical fiber distributed sensing techniques demonstrate the promising capability for the purpose of SHM [2]. By installing sensing fibers to target structures, one can obtain abundant structural parameters with high efficiency based on which the assessment of structural integrity is performed. In a previous study, the overall structural response is successfully monitored using Brillouin optical time domain reflectometry [3]. When it comes to the detection and identification of structural damages, however, it is concluded that high spatial resolution is required for the distributed sensing techniques in order to observe abrupt strain distribution variations induced by the damages.

We have developed a distributed sensing technique with high spatial resolution based on optical frequency domain reflectometry (OFDR) [4–6]. We use a long-length fiber Bragg grating (FBG) with a length of 10 cm and interrogate its spectra at an arbitrary location with a spatial interval of less than 1 mm. The sensing range can be expanded by sequentially inscribing the long-length FBGs with a minimum gap between each.

In order to measure the strain distribution which leads to identification of structural damages of interest, various factors have to be considered in advance of the sensor installation such as sensing locations, installation method (for example, bonding or embedding) and tuning parameters for signal processing. The expected strain distribution after damage might also need to be considered a priori so that one can discuss whether the capability of the sensing technique meets the demands for damage identification. In this paper, we introduce a simulation-based design process which models measurement environment and provides expected measurement results, as a result allows theoretical discussion of the sensing feasibility.

2. OFDR

Figure 1 shows the configuration of the OFDR system. The tunable laser source sweeps the wavenumber and inserts the lights into Interferometer 1 and 2. Interferometer 1 provides clock signal based on which the interfered signal of M3 and the FBG is sampled at D2 with a constant interval of wavenumber. We use low reflectivity FBGs in this work. In this case, the following approximate description of the signal at D2, D_2, is sufficient expressed as

$$D_2 = \sum_i R_i(k) \cos(2n_{eff} L_i k), \tag{1}$$

where k is the wavenumber, n_{eff} is the effective refractive index of the fiber core, R_i represents the spectrum reflected at the location where the distance L_i is away from the mirror M3 [7]. A Bragg spectrum at a certain location, Ri, has an accompanying wave whose frequency is proportionate to

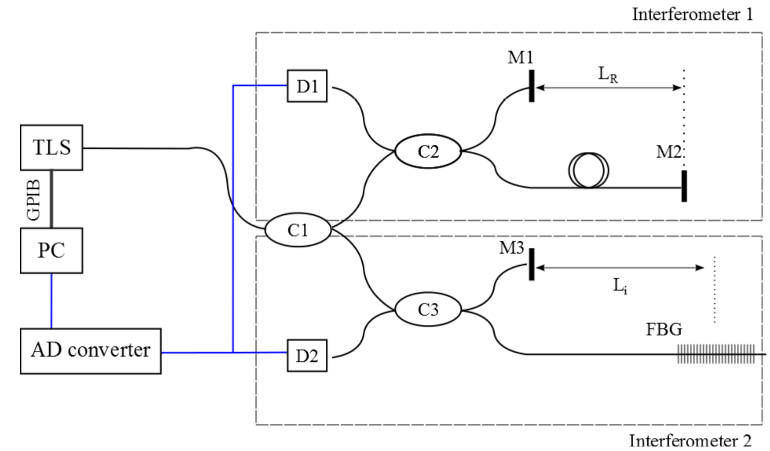

Figure 1: Configuration of OFDR. TLS: tunable laser source, D: photo detector, C: optical 3 dB coupler, M: optical mirror.

the location of the reflection. Therefore, we can demodulate Bragg spectra at arbitrary locations by applying short time Fourier transform (STFT) to D_2.

3. SIMULATION-BASED DESIGN PROCESS

In structural monitoring process, there are various steps which connect the structural parameters of interest (for example, deformation) and the output of the sensing system as depicted in Fig. 2. Deformation yields strains in sensing elements, an FBG in this case. The strains affect the optical response of the FBG. The FBG signal is interfered and detected at a photo detector. Finally, the interfered signal is demodulated into the form of strain through signal processing. A series of numerical simulation model concatenates these steps in the simulation-based design process as seen in Fig. 2.

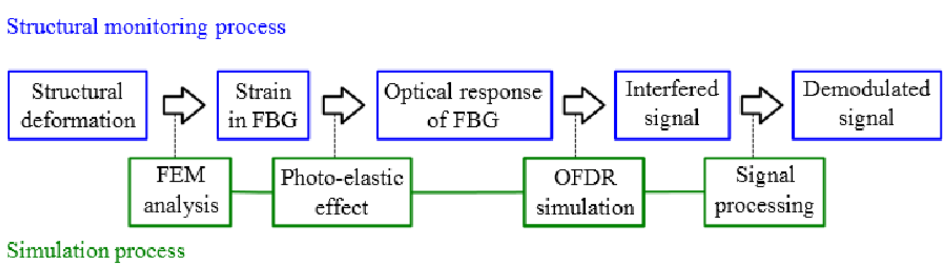

Figure 2: Flow of the structural monitoring process and the simulation-based design process.

We take an example of a tensile loading of an aluminum coupon with holes. The geometry of the coupon is depicted in Fig. 3. The coupon is loaded in longitudinal direction. 7 cm FBG is be bonded, and the 5 cm portion of the FBG is in interest.

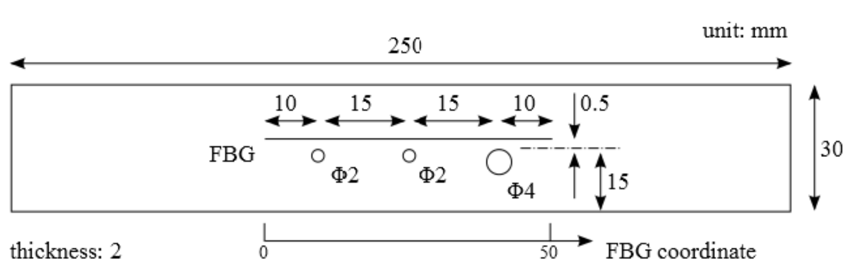

Figure 3: Schematic of the aluminum coupon with three holes.

Firstly, we conduct finite element method (FEM) analysis to calculate strains/stresses which are applied to the FBG as depicted in Fig. 4. Then, we calculate the optical response of the FBG

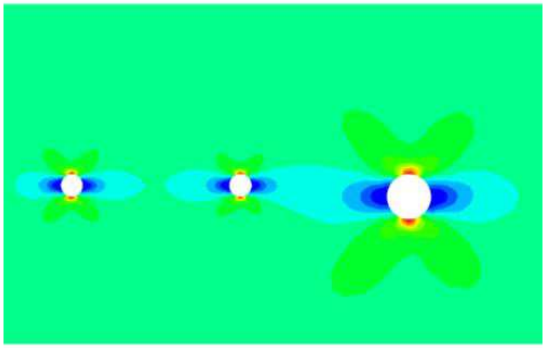

Figure 4: Longitudinal strain distribution around the holes calculated by FEM.

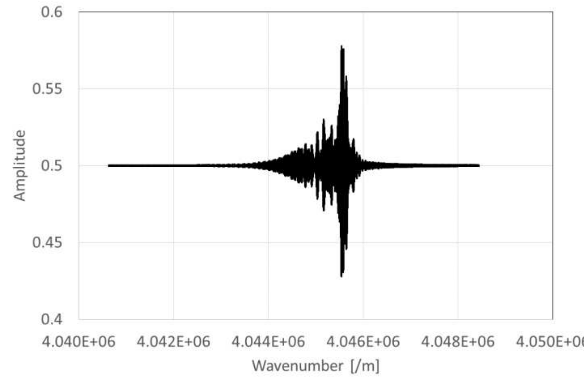

Figure 5: Calculated interfered signal of the loaded coupon with the holes using numerical simulation model of the OFDR system.

based on the equation of the photo-elastic effect which is expressed as

$$\begin{cases} \Delta\lambda_{Bx} = -\frac{n_{eff}^3 \Lambda}{E} \left\{ (P_{11} - 2\nu P_{12}) \sigma_x + [(1-\nu) P_{12} - \nu P_{11}] (\sigma_y + \sigma_z) \right\} + \frac{2n_{eff}\Lambda}{E} [\sigma_z - \nu (\sigma_x + \sigma_y)] \\ \Delta\lambda_{By} = -\frac{n_{eff}^3 \Lambda}{E} \left\{ (P_{11} - 2\nu P_{12}) \sigma_y + [(1-\nu) P_{12} - \nu P_{11}] (\sigma_x + \sigma_z) \right\} + \frac{2n_{eff}\Lambda}{E} [\sigma_z - \nu (\sigma_x + \sigma_y)] \end{cases}, \quad (2)$$

where $\Delta\lambda_B$ expresses the Bragg wavelength shift, L the grating pitch, E Young's modulus and ν the Poisson's ratio of the optical fiber, P the Pockels coefficient and σ the stress. x and y represents the orthogonal axes in the fiber cross-section plane and z represents the longitudinal axis.

The interfered signal at the photo detector in the OFDR system is calculated using the optical response of the FBG obtained previously and the numerical simulation model of the OFDR as shown in Fig. 5 [8, 9]. Finally, STFT is applied to the interfered signal and demodulated signal is obtained in the form of spectrogram as seen in Fig. 6. By extracting the distribution of the Bragg wavelength shifts, one can calculate strain distributions. Fig. 7 shows the strain distributions obtained from the simulation process and an experiment, and the strain distribution calculated by FEM. Longitudinal load of 300 kgf is applied. It can be seen that the simulation process successfully predicts the measurement results.

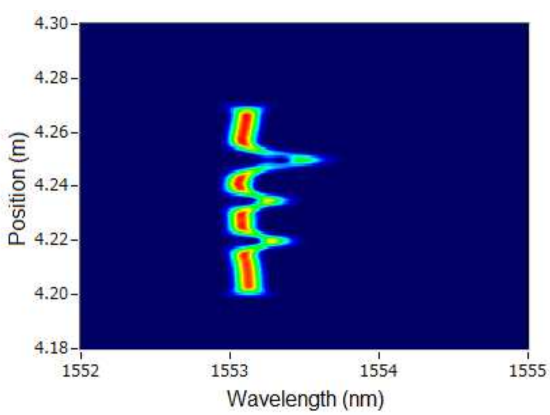

Figure 6: Calculated spectrogram. 7 cm FBG is located at from 4.20 m to 4.27 m.

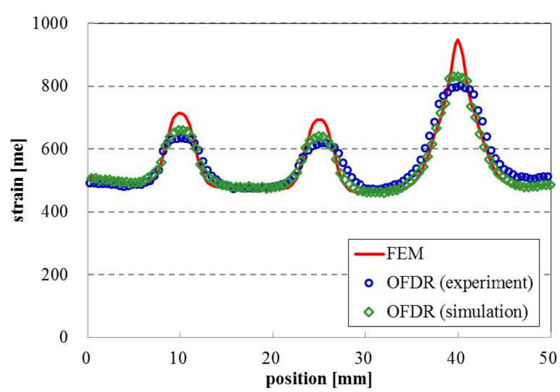

Figure 7: Strain distribution of the coupon with three holes.

4. CONCLUSION

This paper showed that the simulation-based design process successfully predicted the measurement results. Individual simulation steps can calibrate effects of individual steps of structural monitoring process on the output of the OFDR measurement. Therefore, this process can contribute to various discussions regarding SHM such as the optimal sensor location, installation method, tuning parameters for signal processing, noise effect and interpretation of unpredicted signals.

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