

論文の内容の要旨

Thesis Summary

論文題目: Development of dynamic distributed fiber-optic sensor for multi-parameter sensing
(マルチパラメータ動的計測のための分布型光ファイバセンサの開発)

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1. Introduction

The transportation, infrastructure, energy, etc. are important for people life in the modern world. To guarantee the safety and have a good knowledge of the performance of the engineering structures, researchers have made many efforts, such as developing advanced materials, improving operation and maintenance methods. In recent years, an emerging technology namely structural health monitoring (SHM) are becoming very attractive [1]. A typical SHM consists of permanent, continuous, or periodic monitoring comprehensive information of structures on the changes to material and/or geometric characteristics which affect the general structural performances, to assess the structural condition, help with strategy makings, etc. The representative parameters selected to be monitored heavily depend on factors including the type and the use of a structure, expected loads, material, environmental conditions and possible degradation. In general, they can be mechanical, physical or chemical [2]. The most frequently monitored physical/mechanical parameters are strain, temperature and vibration. Practically, the sensors employed are further required to be available for diverse fields, have high density information collection capability, but have little disturbance to the essential performance of the host structure. Although, conventional electrical sensors can measure most of those parameters. In the last few decades, fiber-optic sensors (OFSs) have made a significant entrance in the sensor panorama. The OFSs sense the external environmental variations by the perturbed propagating/reflecting light through the core of the optical fiber that are sensitive to multiple parameters by the optical loss, gain, phase, spectral shift, etc. Meanwhile their advantages such as small, passive, electricity independent in sensing parts, and immune to electromagnetic interference that have big potential to become the promising technologies in SHM [3-5]. Moreover, the capability for distributed measurement may tremendously reduce the number of sensors that makes the OFS even more efficient [6].

In the research, I focus on the fiber Bragg grating (FBG) based OFSs, and explore their sensing functions mainly for strain, temperature and vibration. In both numerical and experimental studies, it has been proved that by applying the same, optical frequency domain reflectometry (OFDR) based, interrogator, it is possible to achieve efficient measurement of desire parameters in distribution and dynamically. Moreover, the investigation and

validation have shown the possible improvement and exploitation in the future work. Also, the proposed approaches are expected to match the additional preferences for SHM to be such as cost effective, simple and robust.

2. FBG-OFDR System

The key sensing technique in this research is FBG-OFDR system. FBG is a structure with periodic refractive index distribution in the core of the fiber. Injecting spectrally broadband light into the fiber, a narrowband spectral component at the Bragg wavelength is reflected by the grating. According to the Bragg's law, the selected wavelength is expressed by

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the core and L is the pitch of the grating. The FBGs has been reported for the measurements of strain and temperature by the detection of Bragg wavelength shifts induced by corresponding parameters' changes, which is expressed as

$$\Delta\lambda_B = K_\varepsilon\Delta\varepsilon + K_T\Delta T, \quad (2)$$

where K_ε and K_T are the sensitivity coefficients for strain and temperature, $\Delta\varepsilon$ and ΔT are the variations of strain and temperature, respectively [3, 4]. FBG generates the distributed reflection which can be interrogated using technologies including OFDR [7]. Among the two interferometers, the data acquisition of the main one is triggered by the auxiliary one at a constant wavenumber interval $\Delta k = \frac{\pi}{n_{\text{eff}}L_r}$. If we divide the long length FBG into M segments, the beat signal can be expressed as

$$I_{x,y} \propto \sum_{i=0}^M R_{x,y,i}(k) \cos(2n_{x,y}z_i k), \quad (3)$$

where R_i is the Bragg spectrum of the i^{th} segment, z_i is its position, the subscripts x, y represent two polarization axes, respectively. Then, the beat signals are demodulated to reconstruct the information carried by the FBG using various methods [7-9].

3. Numerical simulation

The numerical model consists of 5 main parts: testing field, sensing part, interrogator, demodulator and analyzer. In this study, depending on different cases, the testing field which generates the strain, temperature, and vibration is directly defined or simulated by finite element analysis (FEA). In the sensing part, the initial reflection from FBG sensors are simulated by the transfer matrix method [10]. By considering the OFDR interrogation principle, the beat signal can be obtained. By feeding the random errors into the model, the results with and without error influence are analyzed to estimate the sensing performance. The details of error analysis steps can refer to [11]. The proposed model works through the following parts of the study that has been proven to be an effective tool for computer-aided design and principle verification.

4. Fast Demodulation

Apart from the high spatial resolution and high accuracy, the speed is also very important. Conventionally, the information carried beat signal of OFDR is demodulated using STFT [12] or sliding band-pass filter [13]. In general, their performances are very similar that long computational time is needed. To accelerate the demodulation, a recent work is based on the calculation of group delay. However, the relatively low tolerance to noise limits its applicability. To address this issue, a new demodulation with good balance between speed and noise tolerance (represented by accuracy) is proposed. This method mainly employs the cross correlation, fast Fourier transform (FFT), and more importantly, a newly designed thresholding function based on logistic activation function [9]. As a result, this approach shows good measurement accuracy at noisy condition without sacrificing the spatial resolution and computing speed. As a result, for the same measurement, compared to STFT based method, the computational time can be reduced to $\sim 4.2\%$. This may further improve the applicability of this technology in real-time dynamic SHM.

5. Simultaneous Measurement of Strain and Temperature

From Eq. (1), it is apparent that if there are two FBGs with linear independent strain and temperatures sensitivity vectors $\mathbf{v}_{K,1} = (K_{\varepsilon,1}, K_{T,1})$ and $\mathbf{v}_{K,2} = (K_{\varepsilon,2}, K_{T,2})$, the applied parameters can be retrieved by

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} K_{\varepsilon,1} & K_{T,1} \\ K_{\varepsilon,2} & K_{T,2} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix}, \quad (4)$$

where the subscripts 1 and 2 represent two different sensing Bragg peaks, respectively. To obtain different \mathbf{K} vectors, we may use fibers with different refractive indexes (n) and thermo-optic coefficients (dn/dT). This part introduces two approaches for simultaneous strain and temperature measurement. One of them employs high birefringence (Hi-Bi) FBG and the other one is based on FBGs with different dopants (doped-FBG).

5.1. Hi-Bi FBG Based Method

In PM fiber, the inscribed FBG will reflect the light with a spectral separation due to the different refractive indexes in two orthogonal polarization axes. Meanwhile, the thermo-optical coefficients differ. Mathematically, the relation can be expressed as

$$B = |n_x - n_y|, \quad (5)$$

$$\frac{B}{T_{\text{anl}}} = \left(\frac{dn}{dT} \right)_x - \left(\frac{dn}{dT} \right)_y, \quad (6)$$

where the B is the birefringence, and T_{anl} is the annealing temperature during the fiber drawing. In the previous research, Wada et al. demonstrated the static simultaneous measurement using commercial Hi-Bi FBG. In this study, Hi-Bi FBG with about 60% higher birefringence was applied and successfully achieved true real-time dynamic measurement for strain and temperature distribution [14]. In the simulation and experiment, the results have shown that with higher birefringence, the measurement accuracies are also better. The achieved best accuracies in this approach are 29.1 $\mu\varepsilon$ and 2.9 $^{\circ}\text{C}$ at the spatial resolution of 1.6 mm.

5.2. Doped-FBG Based Method

In the manufacturing of optical fibers, to satisfy the guided-mode condition, materials, such as GeO_2 , B_2O_3 , are doped into the fibers for adjusting the refractive indexes in the fiber core and cladding. Specially, GeO_2 increases the refractive index, while B_2O_3 decrease it [15]. Therefore, it can also be used for constructing the \mathbf{K} matrix. In this study, three types of fibers are selected: pure SiO_2 core fiber (PSi-F), GeO_2 doped fiber (Ge-DF) and B_2O_3 and GeO_2 co-doped fiber (B-Ge-DF). Then, the \mathbf{K} matrices were formed by using three different combinations. Combo-A applied PSi-F and Ge-DF, Combo-B applied PSi-F and B-Ge-DF, and Combo-C applied B-Ge-DF and Ge-DF. As a result, the Combo-C showed the best performances among all three types of combinations. The achieved accuracies (12.6 $\mu\varepsilon$ and 1.6 $^{\circ}\text{C}$) are over 50% improved compared to the Hi-Bi FBG based approach. Additionally, since in total, three types of fibers were prepared, the simultaneous measurement was also conducted using overdetermined systems, which is of the form

$$\begin{bmatrix} \Delta\lambda_{\text{si}} \\ \Delta\lambda_{\text{ge}} \\ \Delta\lambda_{\text{b}} \end{bmatrix} = \begin{bmatrix} K_{\varepsilon,\text{si}} & K_{T,\text{si}} \\ K_{\varepsilon,\text{ge}} & K_{T,\text{ge}} \\ K_{\varepsilon,\text{b}} & K_{T,\text{b}} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix}, \quad (7)$$

where the subscripts, si, ge, and b represent the PSi-F, Ge-DF and B-Ge-DF respectively. Mathematically, this system can be solved by using pseudoinverse matrix, weighted averaged method, or weighted least squares method. As a result, the weighted least squares method is the most robust that have large potential in practical applications. Also, the highest accuracies were achieved to be 11.8 $\mu\varepsilon$ and 1.4 $^{\circ}\text{C}$.

6. Self-evaluation in Simultaneous Measurement

An intelligent sensing system for SHM should produce fast and automatic responses to the critical emergencies based on the sensed environment. Among the requirements, an essential one state that the sensor itself should be able to discriminate the components and sensor failures [16]. Conventionally, it is impossible to achieve the target without the double check using reference sensors. This part introduces a self-evaluation approach for distributed FBG sensors in dynamic simultaneous strain and temperature measurement. The intelligent method is demonstrated using the experiment reported in [14, 17]. It is conducted by PM-FBG-OFDR system. In the

demonstration, by using the error propagation properties, an adaptive algorithm was developed for the self-evaluation of measurement error levels. Since no reference sensors are needed in the approach, it is very valuable for the development of smart sensing or smart structure technologies. Also, the estimated errors can be further applied for noise reduction. The results have shown that compared to commonly used digital filters, the noise reduction is especially effective for ultra large errors.

7. Distributed Vibration Sensing

Fiber-optic techniques on quasi-distributed and distributed vibration sensor (DVS) are also attracting a lot of attention for their excellent potential in SHM, oil and gas pipeline security, etc. [18]. Currently, the most popular approaches for realizing DVS are based on the phase-sensitive optical time domain reflectometry (Φ -OTDR). These systems can offer a high performance, at the cost of complicated setups and the use of high-end/expensive equipment. In this study a quasi-distributed vibration sensing technique using in-line weak reflectors (FBGs, broadband reflectors, etc.) and the previously mentioned OFDR is proposed. When vibrations are applied to different sections on the fiber under test (FUT), the side bands will appear along with the carriers in the position domain distribution. By employing the demodulation process, the vibration signal can be retrieved in corresponding sections. Experimentally, as a result, we achieved measurable vibration frequency from 10 Hz to 30 kHz in 10 fiber sections employing a low repetition rate. The ability of the system to determine the frequency and amplitude of several vibrations is evaluated for different configurations (PZT, speaker, etc.). Apart from that, other characteristics such as linearity, maximum detectable frequency were also examined. Because of the simple arrangement, high detectable frequency, high sensitivity and potential to be extended to tens/hundreds of sensing points, this approach is expected to be highly applicable in various mechanical vibration sensing cases.

8. Conclusions and Future Works

To sum up, the multi-parameter sensing of strain, temperature, and vibration have been successfully examined by using a universal OFDR interrogation system. Driven by advanced numerical model and demodulation methods, the overall performances including the accuracy, speed, and detectable ranges have been apparently improved. Moreover, the validations conducted have shown the potential direction of further system improvement and future applications. In the future, based on current achievements, a more integrated, compact and robust system is expected to be designed and applied for practical applications.

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