Practical Solution of BOTDA Technique Applied in Long-term SHM for Infrastructures

---

ZHI ZHOU[1], JIANPING HE[1], KAI YAN[1], JINPING OU[1,2]

[1]SCHOOL OF CIVIL ENGINEERING, HARBIN INSTITUTE OF TECHNOLOGY, HARBIN, 150090, P.R. OF CHINA;

[2]DALIAN UNIVERSITY OF TECHNOLOGY, DALIAN, 116024, P.R. OF CHINA

ABSTRACT:

Distributed Brillouin sensing Technique represents a new physical approach for temperature and strain measurements, which is based on optical time domain reflectometry (OTDR), and seems extremely promising for Structural Health Monitoring (SHM) and being received most attention. Due to the intrinsic distributed sensing capability, Brillouin can measure the temperature and strain using a single-mode fiber, which retains other typical advantages of Fiber Optic Sensors (FOS). Bare optical fiber is too fragile to be used as a sensor in the engineering field. In order to solve this problem, a newly kind of distributed optical sensors protected by FRP, called distributed FRP optical sensor (DFOS), was put forward. Experiment's results, conducted in the lab where the temperature is constant, has showed that the relationship between the Brillouin frequency shift of the sensor and its corresponding strain has sound linear relationship, which implies that the newly distributed FRP optical sensor is suitable for the application in engineering structures.

Keywords: Brillouin frequency shift, Distributed fiber optical sensor, BOTDA, SHM

INTRODUCTION

Fiber optic sensors, such as fiber Bragg gratings and Fabry-Perot interferometers, have received attention in engineering field which are an emerging technology and show superior performance to conventional sensors in measuring strain, temperature, vibration, displacement and pressure under field conditions. Although fiber sensors now have been widely and successfully used, like their conventional counterparts, they have a major drawback that they only provide information about a localized area of a structure. In order to get the global characteristic of the structure monitored, distributed sensing system based on the Brillouin frequency shift (BFS) is being put forward in the structural health monitoring (SHM), which is more versatile than the currently being used Bragg grating sensors as it is capable of providing continuous strain and temperature measurements simultaneously along a strand of single mode fiber.

Distributed Brillouin fiber sensing has received more and more attention and been widely used in many large structures such as bridges, highways, dykes and so on [1, 2, 3]. And more and more new technologies have come forth along the successful application on the structures. Xiaoyi, Bao used the distributed Brillouin sensor to measure a steel beam, where the spatial resolution of the strain measurement was 0.5m [4], and she used the technology for the inspection of pipeline buckling [5]. Hideaki Murayama etc. used the distributed optic fiber sensor to monitor the IACC yachts for America’s Cup 2000[6]. In China, Professor Shi Bin and his group have done much work about the distributed Brillouin scattering optic sensor based on the BOTDR [7, 8].

The distributed Brillouin scattering sensing technique, which can be employed to determine locations and values of desired parameters along the fiber, makes use of optic fibers that are used for both measurement and data transmission purposes, but pass experience has shown that the bare optical fiber is too fragile to act as a sensor in the engineering field. Therefore, in order to solve this problem the bare optical sensor encounters, a newly kind of distributed optical sensor protected by FRP was put forward in this paper. A strain/temperature analyzer DiTeSt (Omnisens) based on the BOTDA technique is employed to measure the Brillouin frequency shift of the sensor, and the experiment’s result showed that the relationship between the Brillouin frequency shift of the sensor and its corresponding strain has sound linear relationship. And the experiment further shows that the new distributed optical sensor is suitable for the large and long-term structural health monitoring.

PRINCIPLE OF DISTRIBUTED FIBER OPTIC SENSING SYSTEM

The distributed fiber optic system (BOTDA) based on Brillouin scattering is based on the interaction of a probe pulse laser and a counter-propagating continuous wave laser. When two laser beams interact inside the fiber, the amplified Brillouin signals will be generated in the opposite direction if the frequency difference between two lasers is the Brillouin frequency of the fiber at the specific temperature and strain conditions. The distributed BOTDA sensing technique makes use of optic fibers that are used for both measurement and data transmission purposes. The optic fiber sensing techniques, similar to that of the traditional optical time domain reflectometer (OTDR), can be employed to determine locations and values of desired parameters along the fiber. And Brillouin frequency shift, v_B and is given by

$$v_B = \frac{2nV_A}{\lambda_i}\sin\frac{\theta}{2} \tag{1}$$

Where n is the refractive index of the fiber, V_A the acoustic velocity of the fiber, λ_i is the wavelength of the incident light and θ is the angle between the incident and scattered light. In this paper, a single-mode optical fiber is considered so that the angle, θ between the reflex and the incident light is $180^o C$ .So equation (1) is changed as the follow:

$$v_B = \frac{2nV_A}{\lambda_i} \tag{2}$$

From this frequency relationship we know that Brillouin frequency varies as strain/temperature changes, as both n and V_A will change when the strain/temperature of the fiber is varied. As long as the characteristic of the fiber is known, the Brillouin frequency and temperature/strain relation can be calculated. The relationship between the Brillouin frequency shift at a certain location (within the spatial resolution) and its corresponding strain or temperature has a sound linearly relationship, described by the following equation:

$$T = C_T\left(v_B - v_{B0}\right) + T_0,\ \ \varepsilon = C_\varepsilon\left(v_B - v_{B0}\right) + \varepsilon_0 \tag{3}$$

Where T is temperature, C_T is the temperature/Brillouin shift coefficient of the fiber, ε is strain, C_ε is the strain/Brillouin shift coefficient of the fiber, v_B is the Brillouin shift of the fiber and v_{B0}, T_0 and ε_0 are values at an arbitrary reference fiber state .

DESIGN OF DISTRIBUTED FRP OPTICAL SENSOR

In order to tackle the problem the bare optical fiber encounters, a newly kind of distributed optical sensor protected by FRP, called distributed FRP optical sensor, was put forward in this paper. This sensor is made by embedding the bare fiber into the FRP, which can escape from the mechanical damages and the chemical reaction between the fiber and the structures. Two kind of distributed FRP optical sensors with different length were developed in this paper. One is 500mm; the other is 1000mm, shown as figure 1. Both sensors have two anchors with 50mm length, and the diameters of the sensors are 3mm. This kind of sensor is suitable to be embedded into the structures such as concrete structure and so on, and the sensor can not easy slide in the structure due to the function of the anchors.

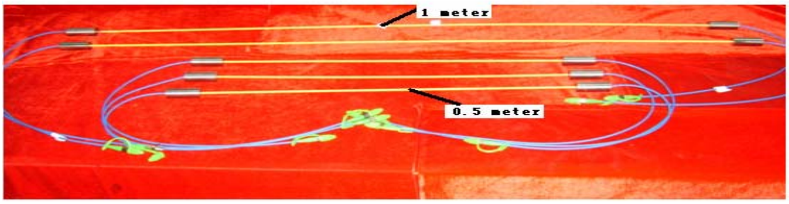


Figure 1: Picture of Distributed FRP optical sensors.

CALIBRATION OF THE DISTRIBUTED OF THE DISTRIBUTED FRP OPTICAL SENSOR

Calibration of the Distributed FRP Optical Sensor with 1m Long

Here distributed FRP optical sensor was calibrated by the system of hydraulic pressure, depicted as Fig. 2. A strain/temperature analyzer DiTeSt (Omnisens) based on the BOTDA technique developed by Omnisense is employed to measure the Brillouin frequency shift of the sensor, which has the best characteristics: the spatial resolution achieves $0.5m$, the strain measurement accuracy is $\pm 20\mu\varepsilon$, and the temperature resolution achieves $1^0 C$. According to the range of the spatial resolution and the distance resolution of BOTDA, two groups of tests were done. The condition of the first test was that the resolution was 1m, and the distance resolution was 0.1m. And the condition of the second one was that the spatial resolution was 0.5m and the distance resolution was 0.1m too.

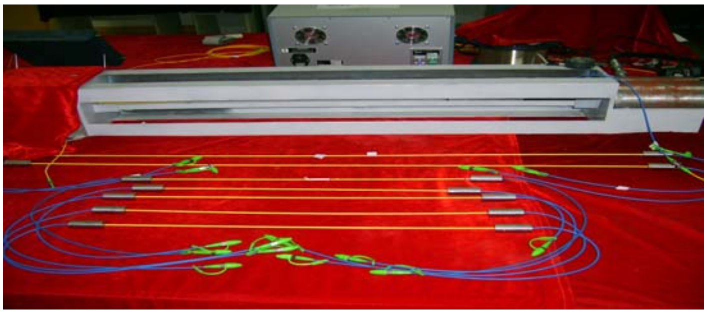


Figure 2: System of hydraulic pressure for the calibration of distributed FRP sensor

Both tests were conducted in the lab where the temperature was constant (about 30 degree), so the influence of temperature needed not to be considered in this paper. Each sensor has been tensioned two cycles, and the step of the strain was about 100~200 micro-strain. The Brillouin frequency shift of the sensor and the corresponding strain were noted. In order to obtain the relationship of the Brillouin frequency shift and the corresponding strain, the middle point of the sensors were chosen to calibrate the sensors. The results of calibration were shown in Fig.3 and Fig.4 respectively.

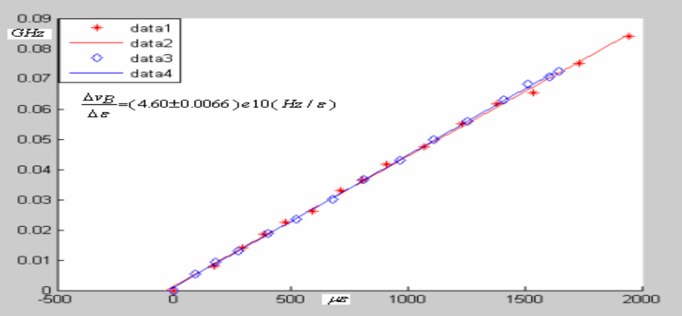


Figure 3: The relationship of the BFS and its corresponding strain with 1m spatial resolution and 0.1m distance resolution.

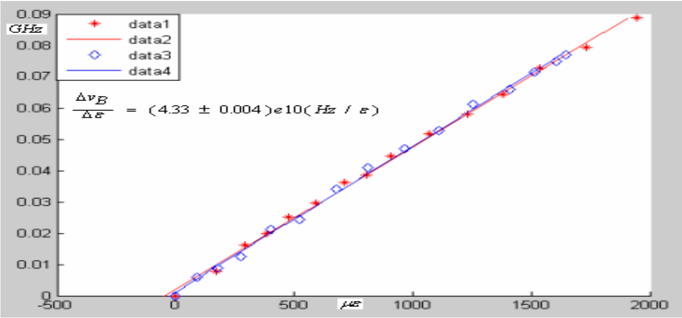


Figure 4: The relationship of the BFS and its corresponding strain with 0.5m spatial resolution and 0.1m distance resolution.

The results of calibration showed that the Brillouin frequency shift of the sensor has good linear relationship to its corresponding strain. The first test showed that the proportion of the Brillouin frequency shift and the corresponding strain was as following equation:

$$\frac{\varepsilon-\varepsilon_0}{\nu_B-\nu_{B0}} = (2.175 \pm 0.03)e-11(\varepsilon / Hz) \qquad (4)$$

or

$$\frac{\nu_B-\nu_{B0}}{\varepsilon-\varepsilon_0} = (4.60 \pm 0.0066)e10(Hz / \varepsilon) \qquad (5)$$

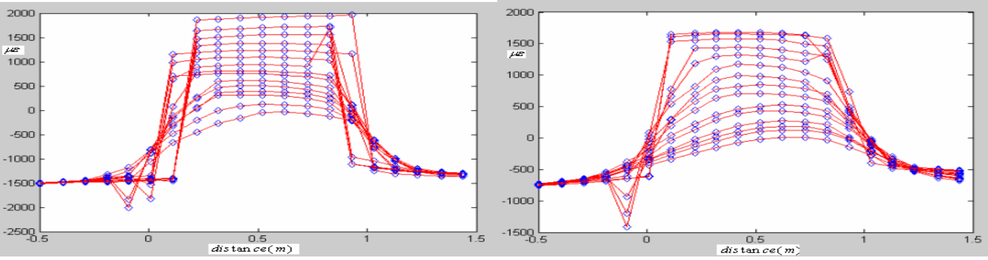
, and the second one was as following equation:

$$\frac{\varepsilon-\varepsilon_0}{\nu_B-\nu_{B0}} = (2.310 \pm 0.03)e-11(\varepsilon / Hz) \qquad (6)$$

or

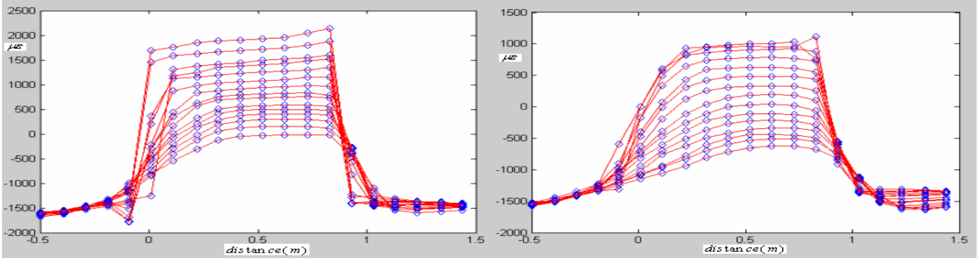
$$\frac{\nu_B-\nu_{B0}}{\varepsilon-\varepsilon_0} = (4.33 \pm 0.004)e10(Hz / \varepsilon) \qquad (7)$$

From the results of the calibration, we can obtain that different spatial resolution had small discrepancy on the proportion of the BFS and its corresponding strain. During the process of application, a suitable spatial resolution should be chosen, for the better higher spatial resolution are chosen, the more measurement time are taken. According to the relationship of the Brillouin frequency shift and its corresponding strain, the strain at every point of the sensor can be obtained, depicted as Fig.5 and Fig.6. From these two figures, we can find that the strains at middle part of the sensors were consistent as the strain increased, and the strains at other parts of the sensors were smaller than the strains at the center part. This shape of the strain explained the fact that The Brillouin frequency shift measured at a particular spot is not the exact value right at that spot, rather it represents the average frequency shift covering the whole length of the pulse, or in otherterms the gauge length over which the measurement is made.



a. The first tension cycle b. The second tension cycle

Figure 5: The strain at every point of the sensor with 1m resolution and 0.1 m distance resolution



a. The first tension cycle b. The second tension cycle

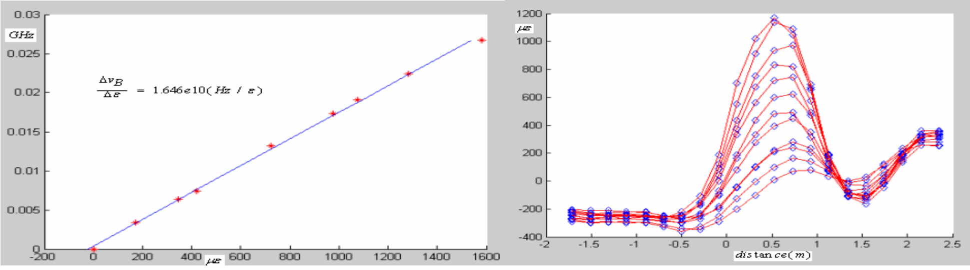
Figure 6: The strain at every point of the sensor with 0.5m resolution and 0.1 m distance resolution

Calibration of the Distributed FRP Optical Sensor with 0.5m Long

The test conditions were as same as the test conditions of the one meter long sensor, the influence of the temperature on the sensor didn't be considered too. Here according to the difference of spatial resolution and distance resolution, two groups of tests were done. The condition of the first test was that the spatial resolution was one meter, and the distance resolution was 0.2m. And the condition of the second one was that the spatial resolution was 0.5m and the distance resolution was 0.2m. The results of calibration were following equations, and depicted as Fig.7 and Fig.8 respectively.

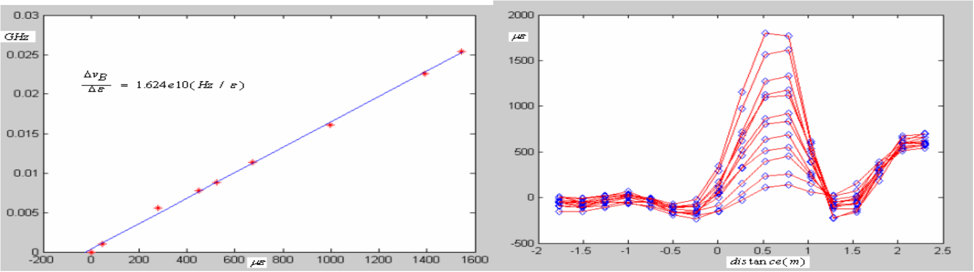
$$\frac{\varepsilon-\varepsilon_0}{v_B-v_{B0}}=6.076e-11(\varepsilon/Hz),\ \frac{v_B-v_{B0}}{\varepsilon-\varepsilon_0}=1.646e10(Hz/\varepsilon) \qquad (8)$$

$$\frac{\varepsilon-\varepsilon_0}{v_B-v_{B0}}=6.159e-11(\varepsilon/Hz),\ \frac{v_B-v_{B0}}{\varepsilon-\varepsilon_0}=1.624e10(Hz/\varepsilon) \qquad (9)$$



a. The relationship of the BFS and strain b. The strain at every point of the sensor

Figure 7: The result of the fist group test with 1m spatial resolution and 0.2m distance resolution



a.The relationship of the BFS and strain b. The strain at every point of the sensor
Figure 8: The result of the fist group test with 0.5m spatial resolution and 0.2m distance resolution

The reason, why the result of the calibration differed mostly from the result of the sensor with one meter length, is that the spatial resolution equal to the length of the sensor. So the value of the strain at some point varied from the exact value at that point.

CONCLUSIONS AND REMARKS

A new kind of distributed FRP optical sensor is brought forward, designed and fabricated, and its feasibility and advantages are set forth. The research results show that the Brillouin frequency shift of this sensor is proportion to its corresponding strain. Test results show that the proportional coefficient varies a little from the discrepancy of the spatial resolution, which implies that a suitable proportional coefficient should be chosen in order to get a sound measurement. The work in this paper is a small step for the application of the distributed FRP optical sensor. There still have a lot of work to be perfected, such as the problem of compensation of the temperature and the methods of the installation of the sensors, and the problem of the signal processing and so on.

REFERENCES

1. Luc Thevenaz, Marc Nikles, Alexandre Fellay. Truly Distributed Strain and Temperature Sensing Using Embedded Optical Fibers. SPIE,1998,3330:301~315
2. A. W. Brown, M. D. DeMerchant, X. Bao, and T. W. Bremner. Advances in Distributed Sensing Using Brillouin Scattering. SPIE,1998, 3330,294~300
3. H. Ohno, H. Naruse, T. Kurashima, etal. Application of Brillouin Scattering Based Distributed Optical Fiber Strain Sensor to Actual Concrete Piles[J]. IEICE Trans. Electron 2002, E85-C(4):945-951
4. Xiaoyi Bao, M. DeMerchant, A. Brown, T. Bremner. Strain Measurement of The Steel Beam With Distributed Brillouin Scattering Sensor. SPIE,2001, 4337: 223~234
5. Lufan. Zhou, Xiaoyi. Bao, etc. Investigation of Brillouin Effects in Carbon Coating Single-Mode Fiber Using for Iinspection of Pipeline Buckling. SPIE, 2005, 6004,Vol 600405-1~05-8.
6. Hideaki Murayama, Kazuro Kageyama, Isao Kimpara. Structural Health Monitoring of IACC Yachts Using Fiber Optic Distributed Strain Sensors: A Technical Challenge For America's Cup 2000. SPIE, 2000, 3986:312~324
7. Gao Jun-qi, Shi Bin,etc. Application of Distributed Fiber Optic Sensor to Bridge and Pavement Health Monitoring. Journal of Disaster Prevention and Mitigation Engineering, 2005, Vol.25 No.1.

8. Dang Zhang, Shi Bin. The Strain Measurement of Tunnel based on BOTDR. Journal of Engineering Geology. 1004-9665/2004/12(04)-0422-05