FBG STRAIN SENSOR WITH SIMPLE TEMPERATURE COMPENSATION MECHANISM

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A FBG-based strain sensor equipped with a mechanical temperature compensation system is proposed. Direct bonding of a FBG element may cause broadening of the reflected optical spectrum due to fluctuation of strain distribution of the material under the FBG element. The proposed sensor avoids this difficulty by introducing a mechanism to induce uniform strain distribution to the FBG element. In addition, a simple mechanical system that can cancel the effect of temperature on the strain measurement eliminate the need for another FBG sensor for temperature compensation. Extensive tests have been conducted using prototype sensors. The results showed their excellent performance.

Key Words : *FBG sensor, strain measurement, temperature compensation*

1. INTRODUCTION

A structural health monitoring system may consist of three components, a sensing component, a signal processing component, and a damage diagnosis component. Such a system is expected to reduce life cycle costs of civil and building structures¹⁾.

Sensors for structural health monitoring systems require following features:

- a. distributed sensing
- b. reasonable costs
- c. durability equivalent to structural life
- d. embeddable to structural components

For example, most popular strain sensors at present, foil gauges, do not have enough durability compared to the service life of the structural system. For the strain measurement, fiber Bragg grating (FBG) sensors are good candidates²⁾. They are durable and small. In addition, they can be multiplexed on a single optical fiber.

However, direct bonding of an FBG element to the object structure to obtain strain values poses several problems. The spectrum band width may be broadened by fluctuation of strain distribution of the material under the FBG element (**Fig. 1**). In addition,

Fig. 1 Relationship between strain distribution and output of sensor. Left : uniform strain distribution. Right : non-uniform strain distribution.

the FBG element has thermal effects that deteriorate the accuracy of the measurement.

In this paper, an FBG-based strain sensor with a temperature compensation mechanism is proposed. The sensor induces uniform strain to the sensing element so that very stable measurement is possible even for the object that exhibits an uneven strain distribution.

2. MECHANISM OF FBG STRAIN SENSOR

(1) Sensing mechanism of FBG

The fiber Bragg grating (FBG) is sensitive to the change of physical parameters in the form of wave-

length shift of the reflected light. This wavelength depends on the grating interval and refraction index of the optical fiber's core. The physical parameters that change the grating interval and/or the refractive index of the core thus cause the wavelength shift. The constant of proportion between the wavelength shift $\Delta\lambda$ (pm) and strain ε ($\mu\epsilon$) is typically 12 pm/ $\mu\epsilon$.^{3) 4)}

(2) Basis of FBG strain sensor

For measuring strains it is necessary to introduce a mechanism that relates the change of strains to the change of the grating interval or the refractive index.

The simplest mechanism is direct bonding of an FBG element. Strains caused by a tensile force extend the grating interval of the FBG element. The strains due to a compressive force reduce the interval. Uniform strains caused by a tensile or a compressive force have linear relation to the wavelength shift until breakage of the optical fiber. Thus, the strains can be calculated from the wavelength shift. However, this mechanism may result in broadening of the reflected optical spectrum, when the strain distribution along the FBG is not uniform. (See Fig.1)

The wavelength shift is also caused by the change of temperature. Thus the FBG strain sensor is also temperature dependent. The changes due to the temperature cannot be distinguished from the wavelength shift if no other information is available. The change of wavelength reaches 9.8 $\mu\epsilon$ for 1 degree Celsius change^{3),4)}. Therefore, the temperature compensation should be included in the strain sensor mechanism. Otherwise, another FBG is needed for the temperature compensation.

In this paper a mechanism is proposed to induce a uniform strain distribution to the sensor and to implement an automatic mechanism for temperature compensation without adding another FBG element. To induce a uniform strain distribution, an FBG element is bonded to a sensor base at the two ends of the element so that the average strain between two bonding points can be measured.

Fig. 2 Configuration of FBG.

The mechanism to compensate the temperature effects utilizes heat expansion of a substance.

(3) FBG strain sensor supported at two points

An FBG-based strain sensor supported at two points is proposed as shown in Fig. 3. This configuration avoids non-uniform strain distribution in the FBG element, as the FBG element is not directly bonded to the target object. In addition the FBG element is stretched to introduce a certain tensile force for enabling compressive strain measurement by this configuration.

An optical fiber in the proposed strain sensor is supported at two bonding points at a sensor base. This configuration can prevent sensor outputs from being affected by non-uniform strain distribution of the material under the FBG element. In other words, this system keeps the strain uniform for a tensile or a compressive force in the FBG element. The fiber is pretensioned to enable the sensor to measure compressive strains. Pre-tension of the FBG element avoids the buckling of the FBG element due to compressive strain. Thus the change of grating intervals can be also related to the compressive strain.

In this FBG strain sensor, the average strain value between the two bonding points in the target object is equal to the strain value induced in the FBG element. In addition, the strain distribution in the FBG element is uniform. As mentioned above, the wavelength shift $\Delta\lambda$ (pm) can be converted to strain ε ($\mu\epsilon$) produced in a component by the proportional constant, 12 pm/ $\mu\epsilon$.

(4) Mechanism of temperature compensation

The center wavelength of reflected light is temperature dependent. A mechanism using thermal expansion of a material that is different from the sensor base is proposed. Fig. 4 shows the FBG strain sensor equipped with temperature compensation⁵⁾.

An FBG strain sensor with a mechanical temperature compensation system has only one additional element for temperature compensation. This material is bonded to an optical fiber, not to the target object. This mechanism is simple and can be fabricat-

Fig. 3 Proposed FBG strain sensor.

ed easily. The change of temperature result the expansion or contraction of this element. Hence strain is introduced to the FBG. By tuning this strain to cancel the effects of temperature change, the temperature compensation is achieved. The basic mechanism is explained below.

When the temperature changes from T_1 to T_2 , the influence of the temperature compensation element to the FBG element can be theoretically obtained. **Fig. 5** shows a plan of the sensor base and the temperature compensation element. The strain ε_c in the component is defined by

$$\varepsilon_c = \alpha(T_2 - T_1) \quad (1)$$

where α is the thermal expansion coefficient. Compressive stress σ_2 is induced in the temperature compensation element and in the optical fiber. Thus, the strain ε_2 is generated. On the other hand, the influence of the temperature compensation element causes the tensile stress σ_1 and the strain ε_1 occurs in an optical fiber.

If expansion and contraction of the element is transmitted to the FBG element without loss, following equations are obtained.

$$\varepsilon_1 L_1 = \sigma_1 \frac{L_1}{E_1} \quad (2)$$

$$\varepsilon_2 L_1 = \sigma_2 \frac{L_1}{E_2} \quad (3)$$

where E_1, E_2 are the young's modulus of the optical fiber and the temperature compensation element, respectively. If the optical fiber is completely adhered to the temperature compensation element, the

Temperature compensation element

Fig. 4 Temperature compensation mechanism.

Temperature compensation element

Fig. 5 Plan view of sensor base.

amount of change of each length becomes

$$\sigma_1 \frac{L_1}{E_1} = \alpha L_1 (T_2 - T_1) + \sigma_2 \frac{L_1}{E_2} \quad (4)$$

It can be assumed that the tensile load $\sigma_1 S_1$ in the optical fiber equals to the compressive load $\sigma_2 S_2$ in the temperature compensation element as

$$\sigma_1 S_1 + \sigma_2 S_2 = 0 \quad (5)$$

where S_1, S_2 are the cross-section of the optical fiber and the temperature compensation element, respectively. From Equations 4 and 5, the strain ε_1 in the optical fiber is expressed as

$$\varepsilon_1 = \frac{\alpha(T_2 - T_1) S_2 E_2}{S_1 E_1 + S_2 E_2} \quad (6)$$

Consequently, the strain ε_2 in the FBG element is defined by

$$\varepsilon_2 = \frac{\varepsilon_1 L_1}{L_2} = \frac{\alpha(T_2 - T_1) S_2 E_2}{S_1 E_1 + S_2 E_2} \frac{L_1}{L_2} \quad (7)$$

Then, wavelength shift λ_{strain} is given by

$$\lambda_{strain} = 1.2 \frac{\alpha(T_2 - T_1) S_2 E_2}{S_1 E_1 + S_2 E_2} \frac{L_1}{L_2} \times 10^6 [pm] \quad (8)$$

On the other hand, 1 degree Celsius, can be converted to the wavelength shift by the constant of proportion, 9.8 pm/. Thus the wavelength shift λ_T [pm] due to thermal crosstalk is given by

$$\lambda_T = 9.8(T_2 - T_1) \quad (9)$$

From the above theoretical derivation, it is clear that the wavelength shift can be defined using eq.8 and eq.9. In the case of temperature rise, the temperature compensation element expands, and induces a compressive strain. As a result, the reflective wavelength shifts to the lower wavelength. On the other hand, the wavelength due to temperature change shifts to the higher wavelength. In the case of temperature drop, the wavelength shift becomes contrary to the case of temperature rise. Thereby, each parameter is determined so that Equations 8 and 9 become equal. This means that choosing an appropriate temperature compensation element an FBG-based strain sensor equipped with a temperature compensation mechanism can be made.

From Equation 8, it is understood that L_1 and S_1 are important parameters for the proposed temperature compensation mechanism. These parameters control the size of temperature compensation element. In terms of the influence to wavelength shift, the expansion is proportional to the size. The sensor size L_1 and S_1 should be as small as possible. The cross-section S_1 and length L_1 are obtained by minimizing Equation 10.

$$f = (\lambda_T - \lambda_{strain})^2 \quad (10)$$

3. PROTOTYPE AND VERIFICATION

(1) Prototype FBG strain sensor

For the performance evaluation of the proposed FBG mechanism, several prototype sensors were designed and fabricated.

In the sensors, the sensor base is used for introducing a tensile force to an FBG element for enabling measurements of compressive strains. In the prototype sensors, the maximum measurable compressive strain was set at 1,000 $\mu\epsilon$. The pre-tension was introduced accordingly. The wavelength shift is 1.2 pm for 1 $\mu\epsilon$. Then, a tensile force needed is approximately 91.5 g. The wavelength shift corresponds to 1.2 nm. In fabricating prototype sensors, the wavelength shifts were monitored to induce the required tensile force in the FBG elements.

The tensile force is introduced by bending the sensor base slightly in the first step. The second step is to bond an optical fiber to this sensor base. The required pre-tension is generated when the sensor is attached to a target object as the sensor base is flattened. The relation between the amount of bending of a sensor base and tensile stress induced in the optical fiber is used to control the amount of pre-tension. This process is explained by **Fig. 6**.

In order to determine the proper material for the sensor base, the rigidity ratios are defined as

$$R_A = \frac{E_B S_B}{E_A S_A} \quad (11)$$

$$R_O = \frac{E_B S_B}{E_O S_O} \quad (12)$$

R_A , R_O represent the rigidity ratio between the sensor base and the target object, and the sensor base and the optical fiber, respectively. The parameters E_B , E_A , E_O are Young's modulus of the sensor base, the target material and the optical fiber. S_B , S_A , S_O are cross-section of the sensor base, the target material and the optical fiber.

The sensor base must be sufficiently soft compared to the target object. If the sensor base is rigid, it will not follow the strain induced in the target object. Therefore, the rigidity ratio defined by Equation 11, must be as small as possible. On the other hand, the rigidity ratio between the sensor base and the optical fiber defined by Equation 12 should be close to or larger than 1 to introduce the proper pre-tension.

In this research, the performance of aluminum plates, acrylic resins and hard vinyl chloride resins are evaluated as candidate materials, to find out the most suitable material as the sensor base.

For the aluminum plate, the rigidity ratio with the optical fiber is 39.21, and is hard enough for transferring the strain to the optical fiber. However the rig-

Fig. 6 Manufacturing process.

idity ratio with the target object, Equation 11, is far bigger than other candidate materials. Thus the aluminum plate is too hard for the sensor base. **Fig. 7** and **Fig. 8** show the rigidity ratios for comparison of acrylic resin and hard vinyl chloride resin, respectively. Considering the rigidity ratio expressed by Equation 12, **Fig. 7** shows that the cross-section of the acrylic resin can be smaller than the hard vinyl chloride resin, and thus it is possible to reduce the size of the sensor base. On the other hand, it is desirable for the rigidity ratio R_A to be as small as possible. **Fig. 8** shows that the acrylic sensor base realizes a better sensor with respect its compactness and the sensitivity.

Based on the test results on three kinds of materials such as aluminum plates, acrylic resin and hard vinyl chloride resin, it is found that the acrylic resin is the best material for the sensor proposed in this paper and hence adopted in fabricating the sensors in the laboratory.

The size of FBG-based strain sensor is represented by length×width×thickness = 40 mm×20 mm×0.5 mm. Young's modulus of FBG element is 7455 kg/mm². The radius of clad is 125 μm (in the case of including coating, 150 μm).

Fig. 7 Rigidity ratio between sensor base and target object.

Fig. 8 Rigidity ratio between sensor base and optical fiber.

(2) Strain measurement experiments

In order to evaluate the FBG strain sensor, strain measurement tests were carried out. The FBG strain sensor was attached to an aluminum specimen. Its size is represented by length×width×thickness = 1000 mm×25 mm×3 mm. Fig. 9 shows the light source. The optical spectrum analyzer is shown in Fig. 10.

The plate was simply supported at both ends. Two cases were considered; tensile strains and compressive strains. The tensile or compressive strains were generated by adding weight at the center of the aluminum plate. The steps of weight increase are 50g, 100g, 150g, and 200g. The center wavelength was measured by the optical spectrum analyzer (OSA). The measured center wavelength is shown in Fig. 11 and Fig. 12. Fig. 13 and Fig. 14 show the experimental setup and equipments. A comparison between Theoretical and measured strain values is shown in

Fig. 9 Light source.

Fig. 10 Optical spectrum analyzer.

Fig. 11 Measured center wavelength before loading.

Fig. 15. This figure compares the amount of strain change with the weight change for every 50g increase or decrease.

The weight was increased by 50g increment up to 200g. Therefore, the strain increase caused by every 50g weight must be constant. The prototype strain sensor was fabricated in our laboratory. Although a primitive fabrication process was employed, it turned out that the measured values were linearly correlated with the weight increase. In the measurement of the tensile and compressive strain, the quantity of strain produced by the weight change of 50 g was 28.33μm - 30μm (maximum change was 1.67μm) in the former, and -30μm - -33.33μm (maximum change was 3.33μm) in the latter. In the range verified in this

Fig. 13 Setup of strain measurement experiments.

Fig. 14 FBG-based strain sensor.

experiment, the linearity was well established. Moreover, in order to check the adhesion state of the FBG sensor after test cycles, the center wavelength was measured at each end of the test cycle. In fact, it did not change at all and was the same with the one before the corresponding test cycle. From this fact it was verified that this FBG-based strain sensor can bear use for many cycles.

(3) Experiment of temperature compensation

A temperature compensation element was mounted on an FBG strain sensor. The target material was cooled and strains were measured by the temperature-compensated sensor and compared with a non-compensated sensor.

Fig. 15 Relation between strain and weight change.

The FBG-based strain sensor is the same as that used in the performance experiments. The temperature compensation element was made by a hard vinyl chloride resin and was bonded to the FBG-strain sensor, as shown in Fig. 16. The size of this temperature compensation element is represented by length $\times$ width = 4.3mm $\times$ 10.6mm based on the discussion in section 2. Fig. 17 shows the setup of experiments. The aluminum plate was cooled by a cooling material until the temperature became stable. Then, the temperature of aluminum plate and the center wavelength of FBG sensor were measured. Fig. 18 shows the effects of temperature change. It is clearly shown that the temperature compensation worked well and agreed with the theoretical value.

From Fig. 18, it is noticed that the temperature dependence is indeed large but can be well compensated by the compensation mechanism. The maximum measurement error was 9pm, this value corresponds to 7.5 μ m in strain. This result verifies the usefulness of this temperature compensation method. On the other hand, when the difference between the temperature of the temperature compensation element and that of the measuring object exists, the temperature compensation does not work properly. Therefore, the time needed for stability of temperature distribution should be taken into account.

Fig. 16 Temperature compensated sensor.

Fig. 17 Cooling test setup.

Fig. 18 Effects of temperature change.

4. CONCLUSIONS

A new FBG strain sensor mechanism was proposed. The proposed sensor can prevent unstable output caused by the direct bonding of the sensor element to a target object. Several prototype sensors were actually designed and fabricated. Extensive performance evaluation was carried out through the strain measurement experiments. A temperature compensation mechanism which is indispensable for the strain measurement using a FBG sensor was also proposed. The performance of the proposed temperature compensation was found excellent.

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