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RESEARCH ARTICLE

Fiber Bragg grating (FBG) strain sensor based on positive and negative double strain body structure

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Abstract Strain monitoring is of great importance for identifying the faults of key mechanical components and ensuring the good operation of mechanical equipment. Aiming at the common problem of low sensitivity of fiber Bragg grating strain sensor in the measurement of mechanical structure surface strain, a fiber Bragg grating (FBG) with a sensitized structure composed of positive and negative double strain bodies is proposed by using a dual-fiber differential measurement scheme. The strain sensor uses the wavelength shift difference of the two FBGs of the positive and negative double strain bodies as the sensing signal to improve the sensitivity of strain measurement on the surface of mechanical equipment and further improve the level of mechanical equipment status monitoring and fault diagnosis. Beryllium bronze with huge elastic coefficient is selected as the substrate material; the sensitivity of FBG strain sensor with positive and negative double strain bodies is analyzed theoretically, and the sensor structure is simulated and designed by SolidWorks and ANSYS Workbench. Based on simulation situation, the real sensor is processed, and the test system is built to test its linearity, repeatability, etc. The results show that the strain measurement sensitivity is 18.26 pm/με, which is about 2.6 times of the reference fiber Bragg grating, the linearity is more than 0.99, and the RSD of repeatability is 2.1%.

Keywords S-shaped sensitization structure · FBG · Positive and negative double strain bodies · Strain sensor

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Introduction

At present, strain is one of the most important and basic physical quantities in the field of structural health monitoring [1]. It is of great practical importance to further improve the level of condition monitoring and fault diagnosis of mechanical equipment by studying high-precision strain sensors for online monitoring and fault diagnosis of mechanical equipment [2, 3]. Nowadays, electromagnetic sensors are widely used to monitor strain. This kind of sensor has a wide range of use and relatively mature technology. Its disadvantage is that it is vulnerable to electromagnetic interference and has a fatigue limit, so it is not suitable for long-term monitoring [4]. As an optical sensing element, FBG has the advantages of light weight, electromagnetic insulation, small volume, and low-fiber transmission loss [5–7]. Therefore, in the field of mechanical equipment fault diagnosis and online monitoring, it can be widely studied and applied, which is conducive to improving the ability of remote online monitoring in harsh environments [8–10].

In recent years, researchers have done a large number research on strain structure and packaging technology of FBG strain sensors and developed various FBG strain sensors. Li et al. [11] designed a strain sensor to measure compressive strain with the sensitivity of − 2.94 pm/με. Peng et al. [12] effectively improved the sensor sensitivity by using lever mechanism and flexible hinge to 11.49 pm/με. Hu et al. [13] proposed a strain sensor consisting of a linear structure and a ring structure with a sensitivity of 38.25 pm/kN. Huang et al. [14] proposed an FBG tension sensor, which uses the wavelength offset difference of two FBGs measuring positive and negative strains in spring elements as the sensing signal, and the sensitivity is 14.85 pm/N. Yang et al. [15] proposed a long-dimension fiber Bragg grating (FBG) strain sensor encapsulated by two T-shaped metal blocks with a sensitivity of 3.2 pm/με. Bian et al. [16] embedded optical fibers with temperature and strain fiber Bragg grating sensors into aluminum casting structures and calibrated the metal embedded sensors for temperature and strain, with a strain sensitivity of 1.27 pm/με. Feng et al. [17] proposed a temperature-compensated multi-point strain sensor based on cascaded FBG and optical FMCW interferometry with a strain sensitivity of 1.16 pm/με. A series of fruitful results have been achieved with FBG strain sensor; however, the low sensitivity of FBG strain sensor has been a bottleneck problem hindering the health monitoring of mechanical structures.

Aiming at the common problem of low sensitivity in optical fiber grating surface strain measurement of mechanical structure, the double-fiber differential measurement scheme is adopted, the mechanical structure of strain sensor is designed, and an optical fiber Bragg grating (FBG) strain sensor composed of positive and negative double strain body is proposed. The beryllium bronze with huge elastic coefficient is selected as the base material, and the sensitivity of FBG strain sensor with positive and negative double strain bodies is theoretically analyzed, and the sensor structure is simulated and designed. Based on simulation situation, a real sensor is processed, and the test system is built to test its linearity, repeatability, etc.

Structural design and sensitization mechanism of sensor

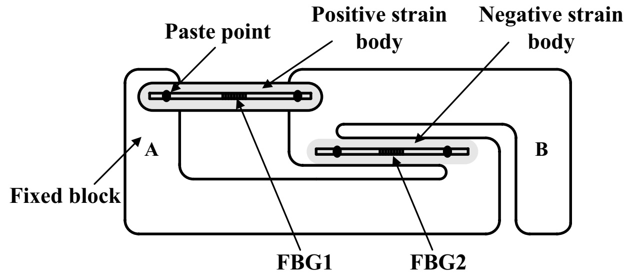
Sensor structure design

The strain sensor mainly consists of four parts with fixed block, positive strain body, negative strain body, and two FBGs. The structural model is shown in Fig. 1. Among them, the regions of positive and negative double strain bodies are thinner than other regions. Theoretically, when tensile force is applied to the sensor, the strain produced in the positive and negative double strain bodies' regions is the largest, FBG1 is in tensile state, while FBG2 is in compression state.

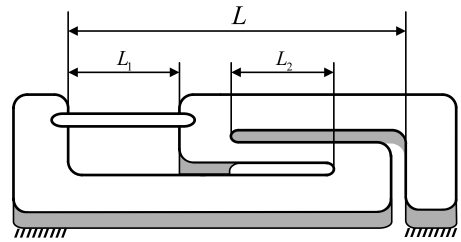
Sensitization mechanism

For a single FBG, it is difficult to distinguish whether the interaction of the strain and temperature in the environment with large temperature difference. Therefore, a dual-fiber differential measurement scheme was used to study the effect of this FBG strain sensor on strain and temperature cross-sensitivity properties.

The dual-fiber differential measurement scheme refers to two identical FBGs pasted on the same sensor, and the central wavelength of two is opposite, one in a stretched state and the other in a compressed state. Assuming that



(a) Top view of sensor model



(b) Front view of sensor model

Fig. 1 Sensor structure diagram

the central wavelength variation of two FBG is, respectively, $\Delta\lambda_a$ and $\Delta\lambda_b$, then the expressions of $\Delta\lambda_a$ and $\Delta\lambda_b$ are

$$\Delta\lambda_a = K_{\varepsilon_1}\Delta\varepsilon + K_{T_1}\Delta T \tag{1}$$

$$\Delta\lambda_b = K_{\varepsilon_2}\Delta\varepsilon + K_{T_2}\Delta T \tag{2}$$

In Eqs. (1) and (2), K_ε represents the strain sensitivity coefficient of FBG, while K_T represents the sensitivity coefficient of FBG to temperature change. By performing the differential treatment of Eqs. (1) and (2), the difference between the FBG central wavelength changes can be calculated as

$$\Delta\lambda_{a-b} = (K_{\varepsilon_1} - K_{\varepsilon_2})\Delta\varepsilon + (K_{T_1} - K_{T_2})\Delta T \tag{3}$$

In formula (3), $K_{\varepsilon_1} = -K_{\varepsilon_2}$, $K_{T_1} = K_{T_2}$, and it is simplified to

$$\Delta\lambda_{a-b} = (\left|K_{\varepsilon_1}\right| + \left|K_{\varepsilon_2}\right|)\Delta\varepsilon \tag{4}$$

According to formula (4), it can be seen that the dual-fiber differential measurement scheme can not only effectively suppress the interaction between FBG strain and temperature, but also improve the sensitivity of the FBG strain sensor.

As can be seen from Fig. 1, when the strain sensor is under tension, the strain ε between the two fixed blocks (A and B) is

$$\varepsilon = \frac{\Delta L}{L} \tag{5}$$

When FBG is subjected to strain $\Delta\varepsilon$, the relationship between strain and central wavelength can be expressed as

$$\frac{\Delta\lambda}{\lambda} = (1 - P_{\mathrm{e}})\varepsilon \tag{6}$$

In Formula (6), λ is the center wavelength of FBG; P_{e} is the effective elastic optical coefficient and the value is 0.22 at room temperature; and $\Delta\lambda$ is the wavelength shift of FBG caused by strain. Further details on FBG can be found elsewhere [18].

The thin region of positive and negative double strain bodies is $L_1 = L_2 = 10$ mm, and the distance between block A and B is $L = 40$ mm. Assuming that the total deformation between block A and B is ΔL, the deformation of the positive strain body is ΔL_1, and the deformation of the negative strain body is ΔL_2, according to $L = 4L_1 = 4L_2$, the strain produced by FBG1 and FBG2 is

$$\begin{cases} \varepsilon_{FBG1} = 4\varepsilon \dfrac{\Delta L_1}{L} \\ \varepsilon_{FBG2} = -4\varepsilon \dfrac{\Delta L_2}{L} \end{cases} \tag{7}$$

According to the dual-fiber differential measurement method, the difference between the two FBG wavelength shifts can be expressed as

$$\Delta\lambda_{1-2} = \lambda(1 - P_e)(\varepsilon_{\mathrm{FBG1}} - \varepsilon_{\mathrm{FBG2}}) \tag{8}$$

Bringing Eq. (7) into Eq. (8), the strain sensitization coefficient K of the sensor can be obtained as follows:

$$K = \frac{4(\Delta L_1 + \Delta L_2)}{\Delta L} \tag{9}$$

As can be seen from Eq. (9), the sensitization coefficient is $K \gg 1$. Therefore, the sensitivity enhancement of the sensor can be realized, and the sensitivity enhancement coefficient K can be adjusted by L_1 and L_2.

Simulation analysis of sensor structure

Sensor simulation analysis

The sensor is modeled by SolidWorks software and imported into ANSYS Workbench for emulation analysis. The material property of the model is beryllium bronze, the elastic coefficient is 128 GPa, Poisson's ratio is 0.35, and the model is meshed. The left and right ends of the sensor are free ends, and the tensile force F of 10 N is loaded on the free end of the sensor substrate to obtain the strain nephogram of sensor, as shown in Fig. 2.

As can be seen from Fig. 2, the strain of sensor is concentrated in the thin region of positive and negative double strain bodies, which bears the deformation of the whole substrate. The positive strain body region is in tensile state, while the negative strain body region is in compression state, with opposite stress direction.

Simulation analysis of sensors and parts to be measured

Static analysis of the overall change of the sensor when the object to be measured is stretched. Use SolidWorks software to establish a 3D model of the part to be measured; the sensor and the part to be measured are formed into an assembly, which is imported into ANSYS Workbench, as shown in Fig. 3a. Fix the left end of the piece to be tested and the right end as the free end. Set a loading surface at the free end and apply a force $F_x = 1000$ N to the right. The displacement deformation nephogram of parts is obtained, as shown in Fig. 3b.

As can be seen from Fig. 3b, the maximum deformation ΔL of the sensor in the x direction is about 0.6424 mm when a force is applied, in which the deformation ΔL_1 in the positive strain body region is about 1.0413 mm and the deformation ΔL_2 in the negative strain body region is about 0.6788 mm. Therefore, the strain sensitization coefficient K of the sensor can be obtained to be about 2.26.

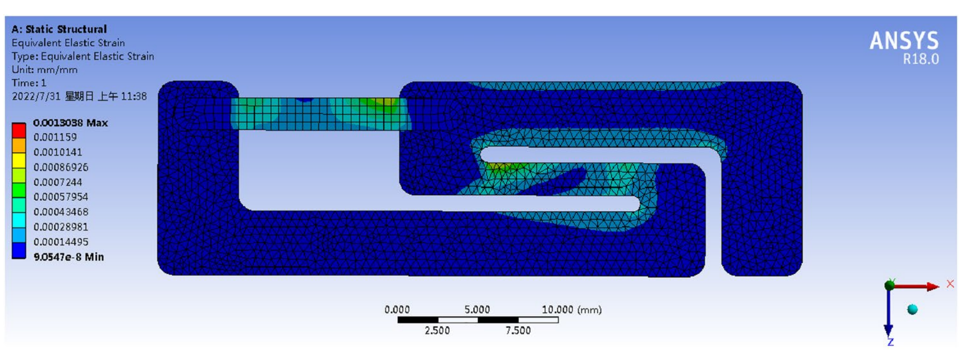
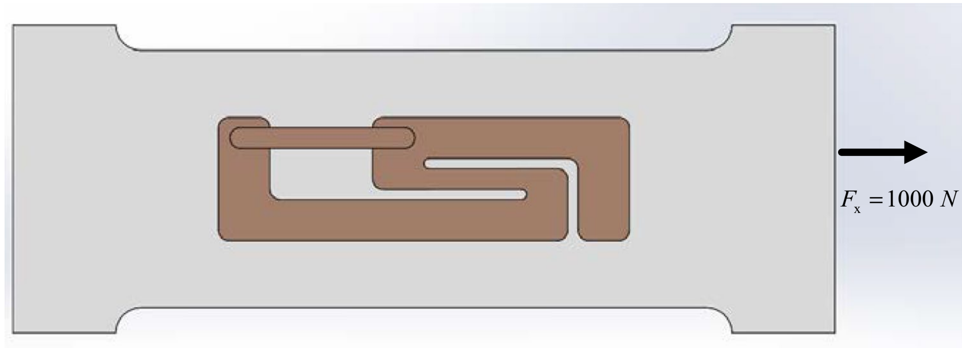
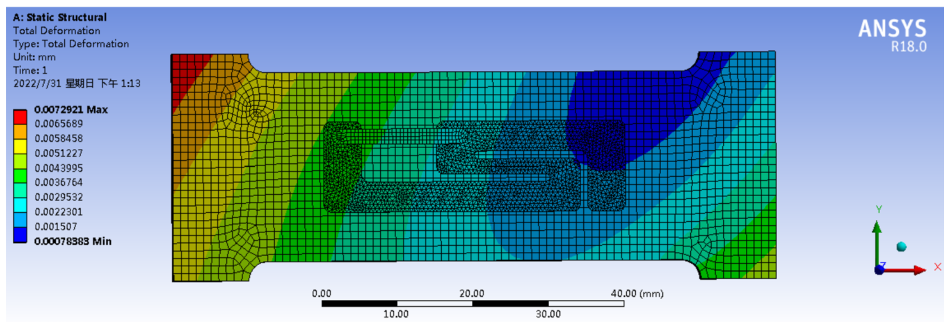


Fig. 2 Strain nephogram

Fig. 3 Sensor simulation analysis



(a) Assembly of parts to be measured



(b) Nephogram of displacement and deformation in tensile state

Table 1 Structural parameters of FBG strain sensor

Parameter	Length	Width	Thickness of positive and negative double strain bodies	Thickness of other regions
Numerical value	40 mm	12 mm	0.1 mm	0.3 mm

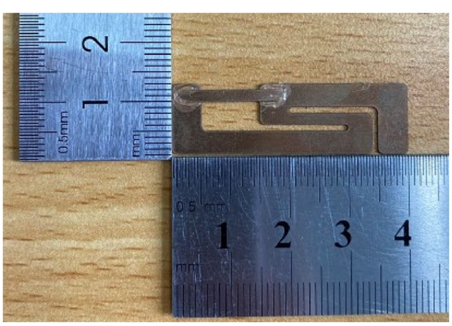


Fig. 4 Picture of sensor

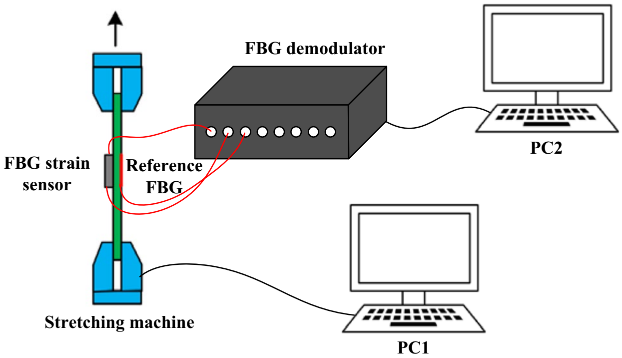
Sensor performance test

According to the theoretical and simulation analysis results, the structural parameters of the developed FBG strain sensor are shown in Table 1, and the physical objects are shown in Fig. 4. The FBG used in the sensor is of the same batch, and its central wavelength is 1550 nm. Relevant parameters of FBG can be found elsewhere [18].

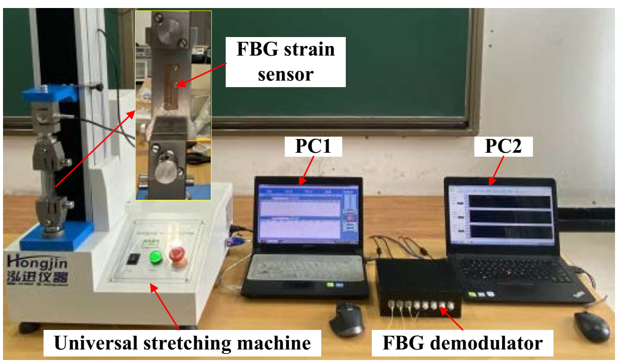
The sensor test system consists of a universal material stretching machine, a FBG demodulator, and two host computers, as shown in Fig. 5. Further details about the FBG demodulator can be found elsewhere [18]. Before the experiment, the FBG1 and FBG2 are pasted between positive and negative double strain bodies by UV glue, and the reference fiber Bragg grating FBG3 is pasted on the substrate of the test piece. It is fixed with the UV lamp irradiation for 40 s, and a certain prestress is applied to the optical fiber when pasting. The universal material stretching machine is HYA-PC-1011B model of Dongguan Hongjin Test Instrument Co., Ltd., its maximum load is 5 kN, the precision grade is 0.5, and the stretching and compression function can be realized by computer control. The system is used to study the linear response characteristics and repeatability of the sensor, and the relevant parameters of the sensor are obtained.

Linearity experiment

To test the linearity and sensitivity of the developed strain sensor, the load is loaded from 0 to 1000 N in 200 N steps. The experimental data are recorded after the center wavelength is stable after each loading. After 1000 N is added, the load is unloaded in 200 N steps and the experimental data are recorded. Taking this as a complete cycle, the



(a) Schematic diagram of the test system



(b) Picture of the test system

Fig. 5 FBG strain sensor test system

variation curve of the central wavelength shift between the developed strain sensor (FBG1–FBG2) and FBG3 with the tension is obtained, as shown in Fig. 6.

It can be seen from Fig. 6 that the strain sensor has a strain measurement sensitivity of 18.26 pm/με and a fitting determination coefficient $R^2 = 0.9991$, while FBG3 has a measurement sensitivity of 7.02 pm/με and a fitting determination coefficient $R^2 = 0.9938$. The experimental results show that the sensitivity of the strain sensor is about 2.6 times that of FBG3, and there is a certain deviation compared with the theoretical value of 2.26. There are two main reasons: First, AB glue and UV glue will creep in the process of stretching; second, in the process of stretching and compression, the fixture of universal material stretching machine will be loose.

Repeatability experiment

The repeatability experiment adopts the same experimental platform as above; the load is loaded from 0 to 1000 N in 200 N steps. The part to be measured is increased from 0 to 1000 N in increments of 200 N and is paused for 10 s in each loading phase. It is then unloaded at the same step size until it is unloaded and also paused for 10 s in each unloading phase. This process is treated as a cycle and repeated three times to test stability. The relative standard deviation RSD is used to represent the repeatability error of the sensor in this test, and it can be expressed as

$$\mathrm{RSD} = \frac{\mathrm{SD}}{\overline{x}} \times 100 \tag{10}$$

In Formula (6), SD is the standard deviation and $\overline{x}$ is the average.

As can be seen from Fig. 7, the sensor can measure the strain on the surface of the object to be measured. The RSD of the FBG central wavelength shift is 2.1%, which shows that the repeatability error of the sensor is relatively small and the stability is good.

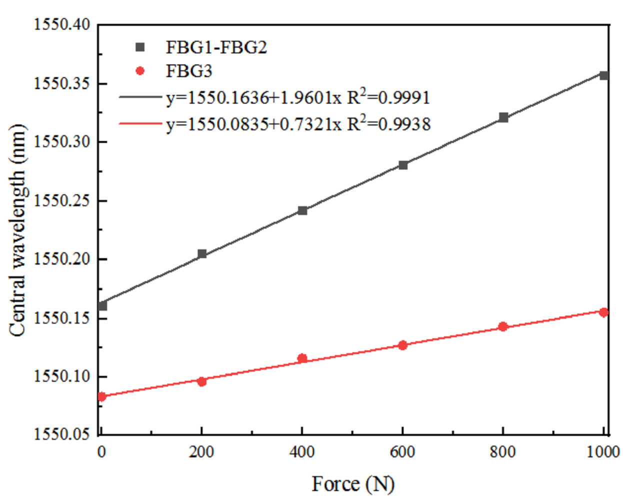


Fig. 6 Effect of tensile force on the central wavelength drift of sensor

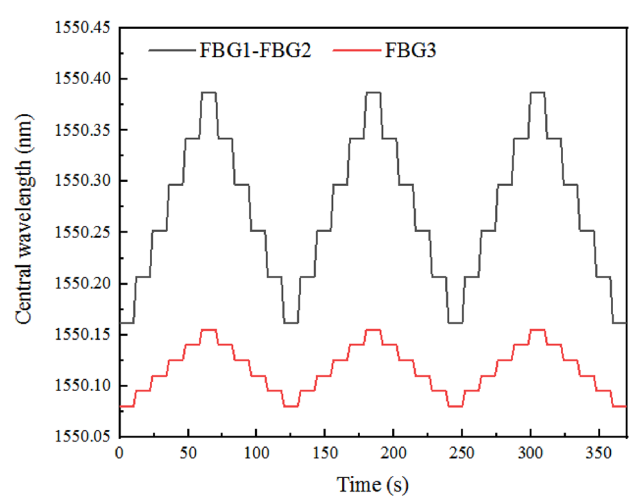


Fig. 7 Repeatability experiment wavelength versus time

Conclusion

Aiming at the common problem of low sensitivity of fiber Bragg grating strain sensor in the measurement of mechanical structure surface strain, a fiber Bragg grating (FBG) with a sensitized structure composed of positive and negative double strain bodies is proposed by using a dual-fiber differential measurement scheme. The sensor uses the wavelength shift difference of the two FBGs of the positive and negative double strain bodies as the sensing signal. Beryllium bronze with huge elastic coefficient is selected as the base material; the sensitivity parameter of the sensor is analyzed theoretically, and the sensor structure is simulated and designed. Based on simulation situation, the real sensor is processed, and the test system is built to test its linearity, repeatability, etc. The results show that the strain measurement sensitivity is 18.26 pm/με, which is about 2.6 times of FBG3, the linearity is more than 0.99, and the RSD of repeatability is 2.1%. In contrast to similar sensors, this sensor has higher sensitivity, better repeatability, and stability, which provides a reference for developing the same type of sensor and further improving the sensitivity of FBG strain sensor. However, since the AB glue and UV glue will creep during the stretching process of the sensor, the sensor may fail in a relatively complex working environment. Therefore, the sensor needs iterative optimization, in order that it can be used in relatively complex fields such as mechanical structures.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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