A temperature-insensitive FBG displacement sensor with a 10-nanometer-grade resolution

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Abstract: This paper proposed and studied a simple and novel displacement sensor that stretching two fiber Bragg gratings (FBGs) directly with a developed lever structure. The sensing principle was presented, and the corresponding theoretical model was derived and validated. Experimental results show that this design has an excellent displacement sensitivity of 23.654 pm/µm and a high resolution of 42 nm within a range of 0~300 µm. The resonant frequency and dynamic working bandwidth of the sensor are 115 Hz and 0~50 Hz respectively, which were obtained through finite element method (FEM) and modal testing experiment. The difference method was utilized to decouple temperature sensitivity of the FBGs, and the experimental results indicate that the designed sensor shows good temperature independence. This sensor can be utilized for micro-amplitude displacement measurement in harsh industry environment.

Keywords: fiber Bragg grating, lever structure, displacement, temperature-insensitive

Classification: Optical systems

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1 Introduction

FBG-based displacement sensors have attracted extensive attention owing to their remarkable advantages such as, miniature size, corrosion resistance, immunity to electromagnetic interference (EMI) and multiplexing capability [1, 2]. Their implementations mainly involve pasting FBG elements on elastic structures to detect displacement. These elastic structures primarily are substrates, cantilever beams and their improved forms.

Substrates are one of the most widely used elastic elements in FBG-based displacement sensors. Li et al. [3] glued the FBG directly on a substrate made of copper beryllium, and utilized a spring element to stretch the substrate to generate stain at the FBG area to detect displacement. As the spring element and the substrate were connected in series, this sensor exhibited a wide displacement measurement range of 550 mm, with a sensitivity of 14 pm/mm and a corresponding resolution of 71.4 µm. Riccardo and Trono [4], and Xia et al. [5], proposed to stick the FBG on a curved elastic substrate, which can enhance the displacement sensitivity and resolution. Further, Tao et al. [6], developed a thin-wall ring (which can be seen as a deeply curved substrate) type FBG displacement sensor with a sensitivity of 567 pm/mm. Correspondingly, its resolution can reach 1.76 µm. Apart from the substrates, the cantilever beams are another widely used elastic structures in the FBG-based displacement sensors. Zhao et al. [7], designed a double-arched-beam-based fiber Bragg grating displacement sensor, but it is not temperature-insensitive. Jiang et al. [8], developed a temperature-insensitive displacement sensor with two FBGs glued on two cantilever beams respectively. Reference [9, 10, 11, 12, 13, 14] all pasted one FBG on the cantilever beam where generated non-uniform strain. This type of sensors can measure displacement and temperature simultaneously. However, these designs either suffer from chirping failures due to the non-uniform strain distribution of the FBG, or experience low resolutions contributed by low demodulation precision of the reflection spectrum bandwidth. These beam-type FBG displacement sensors mentioned above have a resolution level of about 10-micrometer-grade \((10^{-7} \text{m})\) to micrometer-grade \((10^{-6} \text{m})\).

To further improve the sensitivity and resolution, Guru Prasad and Asokan [15] designed a fiber Bragg grating sensor package for sub-micrometer \((10^{-7} \text{m})\) level displacement measurements based on pasting FBG on a curved beam. Li et al. [16, 17, 18] put forward using the transverse property of a tightly suspended optical fiber with FBG to measure displacement. This kind of sensors can overcome the limitations accompanied with the FBG-pasting process and can also realize a high displacement resolution. In the reference [16] and [17], the developed sensors can achieve a resolution of 4.55 µm and 2.04 µm respectively. In reference [18],
they utilized the slope of a wedge-shaped slider to transfer the displacement direction and push the FBG transversely through a T-shaped cantilever beam, realizing sub-micrometer ($10^{-7}$ m) level displacement measurement. However, the friction between the wedge-shaped slider and the T-shaped cantilever beam at the slope reduces its reliability. Besides, some researchers used the FBG itself as the probe to test the displacement [19, 20, 21]. These sensors can achieve 10-nanometer-grade ($10^{-8}$ m) displacement measurement, but they are fragile, temperature sensitive, and have a poor environmental adaptability.

To address these issues, this paper proposed a simple temperature-insensitive FBG displacement sensor to achieve a high resolution at 10-nanometer-grade ($10^{-8}$ m) level. This sensor mainly consists of a developed lever structure and a tightly suspended optical fiber with two FBGs. The developed lever structure forms a conversion mechanism to transfer and regulate the measured displacement into the stretching or contracting of the suspended optical fiber. In section 2, the detail structure of the sensor was introduced, and the theoretical model for the proposed sensing principle was derived with consideration of the conversion mechanism structure. The displacement can be determined by the two FBGs’ reflective central wavelength shift differences and the sensor structural parameters. In section 3, experiments were performed to validate the effectiveness of the derived model. The designed sensor can achieve a high resolution, and the FBG temperature cross-sensitivity was avoided by difference method. Discussions were made in section 4 to compare the advantages and disadvantages of the designed sensor and other existing FBG displacement sensors. Section 5 presented a successful application of the designed sensor in thermal deformation measurement in a heavy-duty CNC (Computer Numerical Control) machine tool. As multiple FBGs can be fabricated in one optical fiber, this designed sensor can be widely utilized in quasi-distributed displacement monitoring.

2 Principle and sensing model

The schematic diagram of the proposed sensor is shown in Fig. 1(a). This sensor mainly consists of a highly suspended optical fiber (Single Mode Fiber, SMF) inscribed with two FBG elements (#1 FBG and #2 FBG), a rotary table, a rod, a probe, and a pedestal. The optical fiber is suspended with a pre-tension force (4 N), and is glued on the rotary table (point A and B) and the pedestal (point C and D). The one end of the rod is bonded on the side surface of the rotary stable, and the other end is bonded with the probe. The probe, rod, and rotary stable forms a lever structure. The optical fiber is connected to a broadband optical source with amplified spontaneous emission (ASE) and an optical spectrum analyzer (OSA) through a 3 dB optical coupler.

When a positive micro-displacement $\Delta d$ is acted on the end of the probe, the probe would drive the rotary table to rotate an angle $\beta$ through the rod. Consequently, the optical fiber fixed point $A$ and $B$ on the rotary table will rotate to point $A'$ and $B'$ respectively. Meanwhile, the end point of the rod $G$ and the end point of the probe $P$ rotate to point $G'$ and $P'$ respectively. As shown in Fig. 1(b), since $\Delta d$ is negligibly small comparing to the structure dimension (the length of the
rod $R$ and the length of the probe $h$) of the designed sensor, the rotating angle of the rotary table $\beta$ approaches zero. Therefore, $\alpha_3 + \alpha_4 = \frac{\pi}{2}$ and $\alpha_1$, we can obtain that $\frac{\alpha_4}{\alpha_2} \approx \frac{\alpha_2}{\alpha_1}$. So the length $PP'$ between point $P$ and $P'$ can be expressed as

$$PP' = \frac{\Delta d}{\sin \alpha_4} \approx \Delta d \cdot \sec \alpha_2 = \Delta d \cdot \frac{\sqrt{R^2 + h^2}}{R} \quad (1)$$

The arc length $\widehat{PP'}$ between point $P$ and $P'$ can be expressed as

$$\widehat{PP'} = \sqrt{R^2 + h^2} \cdot \beta \quad (2)$$

As $\beta$ approaches zero, $\widehat{PP'} \approx PP'$. Therefore, from the equation (1) and (2), we can obtain that

$$\beta \approx \frac{\Delta d}{R} \quad (3)$$

As the optical fiber fixed point $A$ and $B$ on the rotary table rotate to $A'$ and $B'$ respectively, a positive strain $\varepsilon_1$ will generate at #1 FBG, and a negative strain $\varepsilon_2$ will generate at at #2 FBG:

$$\varepsilon_1 = \frac{A'A}{L} = \frac{r \beta}{L} \approx \frac{r}{RL} \Delta d \quad (4)$$

$$\varepsilon_2 = -\frac{B'B}{L} = -\frac{r \beta}{L} \approx -\frac{r}{RL} \cdot \Delta d \quad (5)$$

where $r$ is the radius of the rotary table, $R$ is the effective length of the rod, and $L$ is the effective distance of the two fixed ends of each FBG. The wavelength variation $\Delta \lambda_B$ responses to the strain $\Delta \varepsilon$ and temperature change $\Delta T$ is given by

$$\frac{\Delta \lambda_B}{\lambda_B} = (1 - p_e) \Delta \varepsilon + (a_f + \zeta_f) \Delta T \quad (6)$$

where $\lambda_B$ is the Bragg wavelength of the FBG, $p_e = 0.224$, $a_f = 0.5e-6$ /°C, and $\zeta_f = 6.2e-6$ /°C are respectively the effective photo-elastic coefficient, thermal expansion coefficient and thermal-optic coefficient of the fused silica fiber core of the FBG. Substituting equations (4) and (5) into equations (6), the central wavelength shifts of #1 FBG and #2 FBG caused by the imposed micro-displacement $\Delta d$ and the ambience temperature variation $\Delta T$ can be expressed as follows:
\[
\frac{\Delta \lambda_1}{\lambda_1} = (1 - p_r) \frac{r}{RL} \cdot \Delta d + (\alpha_r + \zeta) \Delta T
\]
(7)

\[
\frac{\Delta \lambda_2}{\lambda_2} = -(1 - p_r) \frac{r}{RL} \cdot \Delta d + (\alpha_r + \zeta) \Delta T
\]
(8)

In equations (7) and (8), \(\lambda_1\) and \(\lambda_2\) are respectively the initial wavelength of #1 FBG and #2 FBG. Temperature rise \(\Delta T\) cause initial wavelengths \(\lambda_1\) and \(\lambda_2\) increase, however, a positive displacement \(\Delta d\) makes the \(\lambda_1\) increase and \(\lambda_2\) decrease. In this designed sensor the two FBGs are fabricated with approximate initial wavelengths \((\lambda_1 = 1555\text{ nm}, \lambda_2 = 1545\text{ nm})\). The initial wavelengths \((\lambda_1, \lambda_2)\) are much larger than the wavelength shifts \((\Delta \lambda_1, \Delta \lambda_2)\), so that \(\lambda_1, \lambda_2\) could be replaced by an equivalence value \(\lambda_0\) (1550 nm). The difference between the two wavelength shifts could be adapted by subtracting equation (8) from equation (7):

\[
\Delta \lambda_1 - \Delta \lambda_2 = \frac{2 r \lambda_0 (1 - P_r)}{RL} \Delta d
\]
(9)

Equation (9) illustrates that the relationship between the \(\Delta \lambda_1 - \Delta \lambda_2\) and the displacement increment \(\Delta d\) is linear. Where \(2 r \lambda_0 (1 - P_r)/RL\) is the displacement sensitivity and is a constant for any given \(r/R\) and \(L\) value. The external displacement in temperature-varying environment can be effectively determined by the central wavelength shift differences of #1 FBG and #2 FBG.

3 Experiments

3.1 Static calibration experiments

The schematic diagram of the experimental setup for calibration and testing is illustrated in Fig. 2. The system consists of a fabricated sensor prototype \((r = 8\text{ mm}, R = 80, L = 88\text{ mm})\), a displacement input iron plate, an FBG interrogator (OPM-T800, Gaussian optics Co., Ltd., China; sampling rate: 1 Hz; resolution: 1 pm), a commercial laser displacement sensor (KEYENCE, LK-H080, resolution: 0.1 µm, precision: 1 µm) with controller, and a screw-feeding structure. The optical fiber was connected to the interrogator to determine the reflective central wavelength of the two FBG elements. The displacement input iron plate was driven by the screw-feeding structure, and then imposed micro-displacement on the probe of the designed sensor. The laser displacement sensor was installed to measure the displacement exerted on the sensor. The displacement
inputs were implemented from 0 to 1 mm with a step of about 50 µm. The
 calibration experiments were repeated 3 times. Fig. 3(a) lists the central wavelength
 shift differences Δλ_1 − Δλ_2 of #1 FBG and #2 FBG at each displacement stage. The
 results demonstrate that the central wavelength shift difference Δλ_1 − Δλ_2 of the
two FBG increases with the increment of displacement Δd. The fitting results are
 presented and the displacement sensitivity is 2.0392 pm/µm within the working
 range 0~1 mm. The fitting linear correlation coefficient reaches 99.442%. This
 sensitivity is in consistency with the theoretical sensitivity 2.7336 pm/µm.

To further enhance the sensitivity, we shortened the length of the rod, making
the R reduce to 8 mm, thus r/R = 1. Experiment was implemented on the second
fabricated sensor prototype with the same instruments and the same processes. The
displacement inputs were implemented from 0 to 300 µm with a step of about
20 µm. As shown in Fig. 3(b), the sensitivity was improved to 23.654 pm/µm
within the working range 0~300 µm. The fitting linear correlation coefficient
reaches 99.863%. This sensitivity is also in consistency with the theoretical
sensitivity 27.336 pm/µm. The reasons for that experimental sensitivities are a
little lower than the theoretical values involve the deformations of the rod and
probe, the gap between the hole in the rotary table and the shaft on the sensor
pedestal, and the low rigidity of the glue. Improving the manufacturing precision
and assembly precision of the sensor’s components will improve the consistency
between the experimental results and theoretical results. The wavelength resolution
of the used FBG interrogator is 1 pm, consequently, this sensor can achieve a high
resolution of 42 nm (0.042 µm). Measurement force is an important property to
use the displacement transducer. According to previous work [17], the single-mode
optical fiber used in the designed sensor can stand an 8 N tensile force. As a 4 N
pre-tension force has already been applied in the packaging process of the sensor,
the designed improved sensor has a measurement force limit of 4 N.

3.2 Dynamic experiments
To investigate the working frequency bandwidth of the improved designed sensor,
a dynamic vibration test experiment setup was established, as shown in Fig. 4(a).
In the experimental system, a vibration exciter was utilized to excite the vibration of
the designed sensor in three directions (axis X, Y, and Z) respectively. The output
signal of the signal generator was sent to the exciter after it was amplified by the power amplifier. The frequency and amplitude of the signal could be adjusted on the signal generator to control the frequency and magnitude of the vibration loaded on the developed displacement sensor. The wavelength shifts of the two FBGs of the sensor were recorded by the dynamic FBG interrogator with a sampling rate of 4 kHz. The resolution of the dynamic FBG integrator is also 1 pm. A commercial accelerometer (B&K, 4507B) was utilized to test the vibration amplitude applied on the designed sensor. Maintaining the vibration amplitude implemented on the designed sensor at 1 g, the vibration frequency was adjusted from 0 to 300 Hz through using the signal generator. Fig. 4(b) illustrates the test results of the designed displacement sensor, which shows that the resonant frequency of the designed sensor is 115 Hz, which is consistent with the finite element method (FEM) result 116.29 Hz by ANSYS software. The designed sensor has a flat response when the applied vibration frequency is less than 50 Hz, which deduces that the working frequency bandwidth of the sensor is 0~50 Hz.

To further verify the dynamic performance of the designed sensor, we used the vibration exciter to implement dynamic displacement on the designed FBG displacement sensor, as shown in Fig. 5(a). The commercial laser displacement sensor (KEYENCE, LK-H080, resolution: 0.1 μm, precision: 1 μm) was utilized as
the reference displacement sensor. Maintaining the peak to peak value of the dynamic sinusoidal displacement implemented on the designed sensor $\pm 2 \mu m$, the frequency of the exciter was adjusted as 0.1 Hz, 1 Hz, and 20 Hz. The comparison results between the laser displacement sensor and the designed sensor are illustrated in Fig. 5(b). The calculated displacement curves of the designed sensor closely matches with the results detected from the commercial laser displacement sensor. Both the signals of the designed sensor and the laser displacement sensor have small distortions, which are caused by the counter-force on the exciter from the designed sensor.

3.3 Temperature compensation experiments

In order to evaluate the temperature-insensitive property of this type of sensor, the variation of wavelength shift difference of the sensor versus temperature increase were tested. The temperature was set to 25 °C, 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, and 85 °C, respectively, and the experiment was repeated for two times. The wavelength shift difference is listed in Fig. 6. As the temperature varies in a wide range, the wavelength shift difference of the two FBGs keeps stable, which indicates that the sensor’s temperature compensation effect is conspicuous.

4 Discussion

The performance comparison of the existing FBG-based displacement sensors is shown in Table I. For the sensitivity column, as the units of the sensitivity in different references are different, most of them use pm/mm as the displacement sensitivity unit, but some others use nm/mm (Ref. [10]) or $\mu m/pm$ (Ref. [15]), which makes it not intuitive to compare. Therefore, we unified their units as pm/mm without changing the real value. For the resolution column in Table I, as the displacement resolution was not only influenced by the displacement sensitivity, but also determined by the central wavelength resolution of the FBG interrogator. In most of the reference papers in Table I, the displacement resolution of the relevant sensor is given when the central wavelength resolution of the FBG interrogator is 1 pm. However, in some other reference papers the displacement resolution is given not under the condition that the central wavelength resolution of the FBG interrogator is 1 pm (marked as #) or the displacement resolution is not provided (marked as *). In order to compare all the sensors’ displacement
resolution impartially, we obtained their displacement resolution through the displacement sensitivity, under the assumption that the central wavelength resolution of the FBG interrogator is 1 pm.

It can be seen from the Table I that, for the traditional substrate type or beam type FBG displacement sensor, the sensitivity can varies from about 10 pm/mm level to about 2000 pm/mm level. Correspondingly, the resolution varies from 100 µm level to sub-micrometer (0.1 µm) level. Unlike the substrate type or beam type FBG-based displacement sensors that involve pasting the FBG on an elastic element, Li et al. [16, 17, 18]'s sensor bonded the two ends of the FBG and using the FBG itself as the elastic sensing element which can achieve a sub-micrometer resolution. As gluing the FBG area was avoided, their sensors can reduce the risk of chirping failures. However, these sensors use a slider to push FBG transversely to sense the displacement. The friction between the wedge-shaped slider and the T-shaped cantilever beam at the slope reduces its reliability, especially when the gradient of the slope is large. References [19, 20, 21] used the FBG itself as the probe to test the displacement, which can achieve 10-nanometer-grade displacement measurement, but they are fragile, temperature sensitive, and have a poor environmental adaptability. Based on the references [16, 17, 18], the proposed sensor also bonded the two ends of the FBG and using the FBG itself as the elastic sensing element to avoid gluing the FBG area. Comparing with refer-

| Items | type | Sensitivity (pm/mm) | Resolution (µm) | Temperature insensitive | Size (mm²) |
|-------|------|---------------------|----------------|------------------------|------------|
| Ref. [3] | Substrate, FBG pasted | 14 | 71.42 (0.13%FS) | ✓ | – |
| Ref. [4] | Curved substrate, FBG pasted | 290 | 3.4 (0.24%FS) | ✓ | 190 x 0.3 |
| Ref. [5] | Curved substrate, FBG pasted | 39.37 | 25 | ✓ | – |
| Ref. [6] | Thin-wall ring, FBG pasted | 567 | 1.76 (0.50%FS) | ✓ | 47 x 47 |
| Ref. [8] | Beam type, FBG pasted | 120 | 8.3 | ✓ | – |
| Ref. [9] | Beam type, FBG pasted | 92.4 | 10.82 (0.40%FS) | ✓ | 82.5 x 30 |
| Ref. [10] | Beam type, FBG pasted | 317 | 3.15 (0.90%FS) | ✓ | 120 x 6 |
| Ref. [11] | Beam type, FBG pasted | 1270 | 0.78 (0.07%FS) | ✓ | 61 x 3 |
| Ref. [13] | Beam type, FBG pasted | 58 | 17.24 (0.86%FS) | ✓ | 150 x 40 |
| Ref. [14] | Beam type, FBG pasted | 250 | 4 (0.26%FS) | ✓ | 170 x 50 |
| Ref. [15] | Beam type, FBG pasted | 2020 | 0.495 (0.08%FS) | – | 72 x 56 |
| Ref. [16] | Slider pushing FBG transversely, FBG 2-end fixed | 219.69 | 4.55 (1.80%FS) | – | – |
| Ref. [17] | Slider pushing FBG transversely, FBG 2-end fixed | 490.1 | 2.04 (3.40%FS) | – | – |
| Ref. [18] | Slider pushing FBG transversely, FBG 2-end fixed | 2086.27 | 0.48 (0.48%FS) | – | 49 x – |
| Ref. [19] | FBG as probe | – | 0.06 | – | 6.19 x 0.25 |
| Ref. [20] | FBG as probe | – | 0.05 (2.00%FS) | – | 12 x 0.51 |
| Ref. [21] | FBG as probe | – | 0.01 (0.40%FS) | – | 12 x 0.51 |
| This paper | Ingenious lever stretching FBG axially, FBG 2-end fixed | 23654 | 0.042 (0.14%FS) | ✓ | 120 x 30 |
ences [16, 17, 18], the proposed sensor avoid the wedge-shaped slider structure, and can achieve a better repeatability and reliability. Comparing with the displacement sensors that use the FBG as the probe in references [19, 20, 21], the sensor proposed in the paper can achieve the same level (10-nanometer-grade) micro-displacement measurement with temperature compensation, and has a stronger environmental adaptability. To compare the performances of these sensors, resolution (or sensitivity) - measurement range ratio and sensor size are also important factor. Therefore, the resolution - measurement range ratio and the out dimensions are also listed in Table I. The size of our sensor is in the middle of all these sensor. The resolution - measurement range ratio of the designed sensor are better than most of other sensors in Table I. Only, the resolution - measurement range ratio of the beam-type sensors in Ref. [11, 15] are about half of our designed sensor. But their resolutions are 10 times larger than our designed sensor. From equation (9), the sensitivity of the proposed displacement sensor can be easily regulated through adjusting the lever ratio \( r/R \) of the lever structure, and the distance \( L \) between the two fixed ends of the FBG. If \( L \) is shortened, or the \( r/R \) rises, the sensitivity and resolution of the designed sensor can be further enhanced. But correspondingly, both the manufacturing accuracy of the components in the sensor and assembly precision of the sensor need to be improved. On the other hand, through increasing the length of \( L \) or reduce the radio of \( r/R \), the displacement measurement range of the sensor can be magnified with a relatively small but adequate sensitivity and resolution.

5 Application in thermal deformation measurement

In precision machining, the thermal deformation error accounts for about 40–70% of the total manufacturing errors [22], making it the main factor that restrict the manufacturing precision of modern machine tools. Traditionally, temperatures at main thermal resources are recorded to establish the thermal error prediction model. However, as the temperature field of the machine tool is dynamic and non-uniform, the precision of the existing thermal error prediction models is poor. Since the formation process of thermal errors in a CNC machine tool occurs in the following steps: heat sources → temperature field → thermal deformation field → thermal errors. It is obvious that the relationship between the thermal deformation field and thermal errors is more relevant than the relationship between the temperature field and thermal errors. Monitoring the thermal deformation of the large-scale structure of the CNC machine tool directly, can be helpful to establish more accurate and more robust thermal error prediction models. The laser displacement sensors or laser interferometers can be used to measure the thermal deformation of machine tools, but they can be easily interfered by environmental factors and have a high economic cost. Here we developed a new method based on the designed sensor to detect the thermal deformation, taking the thermal elongation monitoring of the ram in a heavy-duty CNC machine tool as an example.

As shown in Fig. 7(a). The designed sensor was fixed at the down end of the ram. A SiO2 bar (Diameter 10 mm) was installed on the ram by two magnetic fixers. The magnetic fixer 1 fixed the up end of the SiO2 bar on the ram while magnetic
fixer 2 just restrict the bar to swing. As the thermal expansion coefficient of the SiO2 bar is 5.5e-7 °C, which is pretty smaller than the thermal expansion coefficient of the ram (11.8e-6 °C), the thermal elongation of the SiO2 bar caused by environmental temperature shift can be ignored. The probe of the designed sensor contacts with the down end of the SiO2 bar with a 150 µm pre-displacement. When the environmental temperature changes, the designed sensor detects the thermal elongation of the ram in the case that the CNC machine tool do not operate. Fig. 7(b) illustrates the thermal elongation shift of the ram in one day (24 hours) in winter. The max thermal elongation of the ram in this day is 22.5 µm, which can not be ignored in high precision manufacturing.

6 Conclusion

A novel FBG-based displacement sensor has been proposed and implemented with a high resolution of 10-nanometre-grade. The use of a developed lever structure has been validated to effectively regulate and enhance the sensor’s sensitivity. 1) Experiments have been performed to show that the sensitivity of this sensor can achieve 23.654 pm/µm in a measurement range of 0~300 µm, with a 10-nanometer-grade resolution; 2) The dynamic working bandwidth of the sensor is 0~50 Hz. The comparison results show that the measured dynamic displacement values from the proposed sensor are consistent with these detected from the commercial laser displacement sensor; 3) The temperature cross-sensitivity of FBG is effectively avoided through difference method, which has been verified experimentally. Moreover, this kind of sensor has the advantages of being simple and easy to be fabricated. Therefore, this sensor can be utilized for considerable applications in engineering fields for displacement and deformation detection in temperature-varying environment.

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