

Self-Compensating Displacement Sensor Based on Hydramatic Structured Transducer and Fiber Bragg Grating

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Abstract: An optical fiber displacement sensor with a large measuring range for simultaneous displacement and temperature measurement is presented in this paper. We developed a specific transducer based on the piston and hydraulic structure to realize a large displacement measurement, which combined the large measuring range and high precision into a single sensor system. The spectrum showed two reflection peaks used to compensate for cross-sensitivity in the displacement detection. This displacement sensor can linearly work in a large measuring displacement range greater than 45 mm with a high sensitivity of 0.036 nm/mm. The sensor we reported can be developed for real-time displacement monitoring in many industrial environments such as the mechanical shape or liquid level monitoring.

Keywords: Hydraulic structured transducer, large measuring range, temperature compensating, optical fiber sensor, displacement

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1. Introduction

Optical fiber sensors have emerged as common sensing elements for temperature [1], strain [2], refractive index (RI) [3], force [4], and other parameters measurement, because of their features of anti-electromagnetic interference, corrosion resistance, compactness, lightweight, and high sensitivity, etc. [5, 6]. Being one of the important optical fiber sensors, the fiber displacement sensor has been widely applied. Different types of fiber displacement sensors were demonstrated in the fields of the interferometry [7–9], intensity modulation method [10, 11], and wavelength modulation method based on the fiber Bragg grating (FBG) [12–14]. A fiber displacement sensor based on multimode fiber as a resonant cavity was

reported [9]. However, the interferometry has the feature of low wavelength division multiplexing. A mathematical model for the two-fiber intensity modulated displacement sensor was proposed [10], which was used to simulate the response of the sensor with different inclined fiber angles. Nevertheless, the strain and temperature cross-sensitivity problem could influence the experimental result. To solve this problem, some technologies were proposed. A type of improved FBG sensors was reported [13]. It could simultaneously measure displacement and temperature. And the displacement sensing process can be tuned by applying the bilateral cantilever beam. Although the problems of low sensitivity and cross-sensitivity have been solved, most of those displacement sensors are limited by small measuring

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ranges and poor durability. In this paper, we develop an optical fiber displacement sensor. The transducer we designed was constructed by a hydraulic transmission system, which could provide a large displacement measuring range. The dual-wavelength FBG written on a joint point of a single mode fiber (SMF) and a photosensitive fiber (PSF) provides two separate FBG wavelengths for temperature compensation. The sensor we designed featured a large measuring range, high sensitivity, favorable durability and could avoid the cross-sensitivity problem.

2. Principle and system construction

The structure schematic of the displacement sensor based on the hydraulic structured transducer is shown in Fig. 1. The proposed transducer is composed by two oil columns and two pistons with different cross sectional areas. The transducer can transform the large-displacement into the micro-displacement applied on the cantilever

beam. The transducer is a hydraulic transmission system based on the Pascal's principle and can transmit displacement, speed, and power.

Figure 2 illustrates schematics of the optical fiber displacement sensing system. Figure 2(a) shows a sensing system for displacement measurement. The light from a broadband light source (BBS) is launched into the FBG through the coupler, the backward light enters into an optical spectrum analyzer (OSA, AQ6370, YOKOGAWA) through a 3-dB 2×2 coupler, and the sensor is attached on a cantilever beam. The reflection spectrum of the dual-wavelength FBG is shown in Fig. 2(b). Because the FBG is written by using 193 nm excimer laser through a 1065 nm mask on a joint point of the SMF and PSF, two reflection peaks with different central wavelengths can be observed. Both of the two FBG wavelengths can be tuned by physical parameters, thus we use it for simultaneous displacement and temperature measurement.

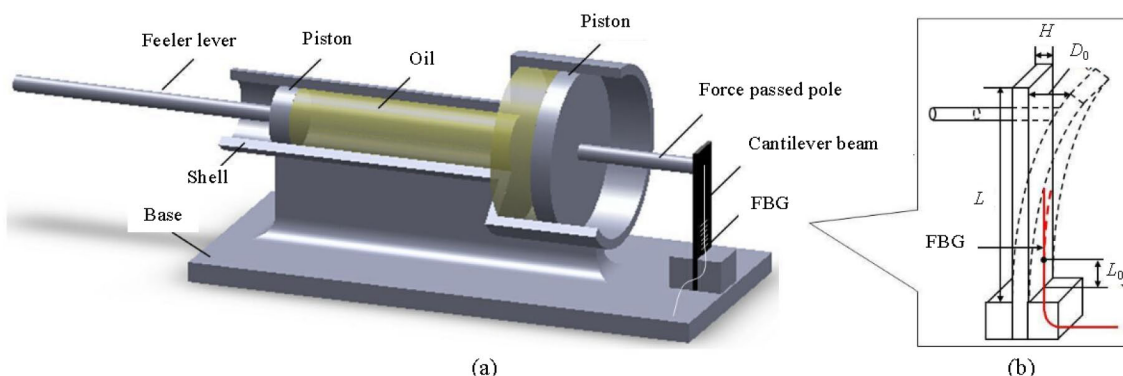


Fig. 1 Experimental setup of the measuring system: (a) transducer based on hydraulic structure and (b) cantilever beam attached FBG.

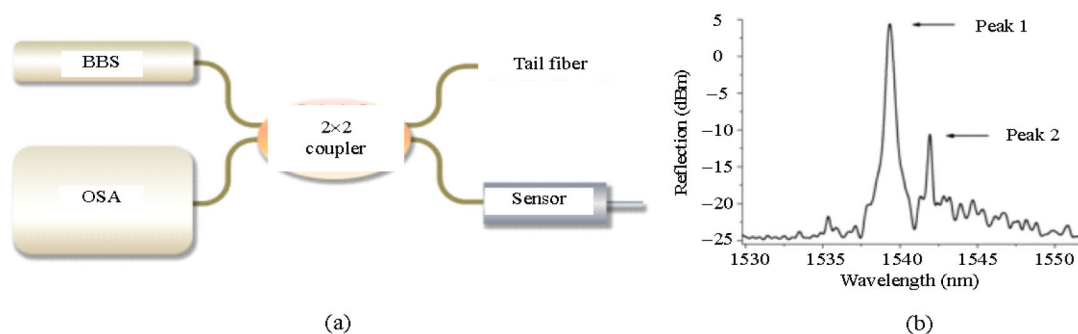


Fig. 2 Schematics of the optical fiber displacement sensing system: (a) sensing system for displacement measurement and (b) dual-wavelength FBG reflection spectrum.

According to the law of volume constancy, the hydramatic transducer can transfer large-displacement D into micro-displacement D_0 by the area difference between two pistons in their respective working chambers, and the relationship can be expressed as

$$S \cdot D = S_0 \cdot D_0 \quad (1)$$

where S and S_0 are the cross section areas of two oil columns. Because the pressures of liquid are equal everywhere, the pressure ratio of two pistons is the same as the area ratio of two pistons, namely the expression is

$$P = P_0 = F/S = F_0/S_0 \quad (2)$$

where P , P_0 , F , and F_0 are pressures and forces of two pistons, respectively. In our experimental setup, the pressure in the feeler lever is $F = F_0/10$ (the range of F is from 7N to 8N) because $S:S_0 = 1:10$. In addition, we can get less F by increasing the cross section area ratio.

The cantilever beam is shown in Fig. 1(b). When the free end of the transducer produces a displacement of D_0 , it will lead to the cantilever beam to be bent. Then, one side of the beam produces tensile strain while the other side of the beam produces compressing strain. According to the previous work [15], assuming λ_1 and λ_2 are the Bragg wavelengths of the FBG, we find the relationship between the wavelength-shift and displacement of the free end is

$$\begin{pmatrix} \Delta \lambda_1 \\ \Delta \lambda_2 \end{pmatrix} = \begin{pmatrix} \Omega_{D_1} & \Omega_{T_1} \\ \Omega_{D_2} & \Omega_{T_2} \end{pmatrix} \begin{pmatrix} \Delta D \\ \Delta T \end{pmatrix} \quad (3)$$

where $\Omega_{D_i} = \partial \lambda_i / \partial D_i$, $\Omega_{T_i} = \partial \lambda_i / \partial T_i$ ($i=1, 2$). As the sensing element (FBG) is composed by different fibers, the deformation responses caused by the displacement are different ($\Omega_{D_1} \neq \Omega_{D_2}$) while the relationship of temperature response is $\Omega_{T_1} \approx \Omega_{T_2}$. Thus the difference of two peaks' wavelength shifts $d\Delta\lambda = \Delta\lambda_1 - \Delta\lambda_2$ is independent of temperature. Assuming $d\Delta\lambda_0 = \Delta\lambda_{10} - \Delta\lambda_{20}$, the relationship between the displacement and wavelength is

$$d\Delta\lambda - d\Delta\lambda_0 = |\Omega_{D_1} - \Omega_{D_2}| \Delta D. \quad (4)$$

Then, the displacement can be expressed as

$$\Delta D = (d\Delta\lambda - d\Delta\lambda_0) / |\Omega_{D_1} - \Omega_{D_2}|. \quad (5)$$

As a result, through monitoring the difference between two FBG wavelength shifts $d\Delta\lambda$, the displacement of the free end (the measured displacement value ΔD) can be measured.

3. Experiments and discussion

In Fig. 1(b), the feeler lever transmits the displacement from the measured object to the free end of the cantilever beam. The length of the beam L was 70 mm, the thickness H was 1 mm, and the FBG was pasted at the place $L_0=5$ mm. The lengths of FBGs written in the SMF and PSF were 1 cm and 3 mm, respectively. The reflective peaks of FBGs written in the SMF and PSF were 1539.188 nm and 1541.624 nm (Peak 1 and Peak 2 as follows). Using the above structure, we made the following displacement measurement at room temperature (20 °C). The displacements of the free end were from 0 mm to 45 mm with a step of 5 mm, and the measured results are plotted in Fig. 3. As the responses of the two Bragg wavelengths decrease linearly, respectively, Peak 1 shifts to the short wavelength at a faster rate than Peak 2, and the experimental values of Ω_{D_1} and Ω_{D_2} were -0.049 nm/mm ($R^2=0.991$) and -0.013 nm/mm ($R^2=0.979$) over the range from 0 mm to 45 mm.

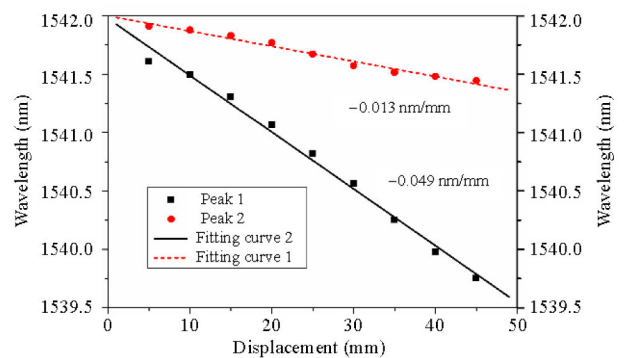


Fig. 3 Responses of dual-wavelength FBG to displacement.

To make sure the measurement result is reliable, the responses of the two Bragg wavelengths of three measurements are shown in Fig. 4, from which we can find the measurement results of wavelength responses to displacement possess good repeatability.

The standard deviations of Peak 1 and Peak 2 were less than 0.084 and 0.064, which indicated the experiment results measured in three rounds had little difference, respectively.

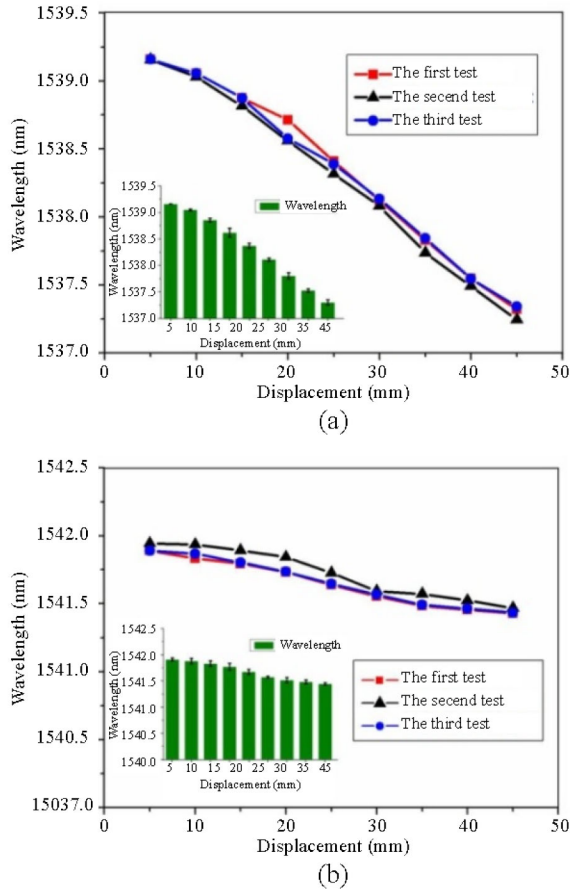


Fig. 4 Repeatability testing of two FBG wavelengths response to different displacements: (a) Peak 1 and (b) Peak 2.

Then, we tested the temperature characteristic of the sensing element in the water bath over a range from 25 °C to 65 °C. As shown in Fig. 5, the two Bragg wavelengths increase with temperature linearly. The experimental values of ΩT_1 and ΩT_2 were 0.036 nm/°C ($R^2=0.995$) and 0.034 nm/°C ($R^2=0.991$) during this temperature range.

Thus, as $\Omega D_1 = -0.049$ nm/mm, $\Omega D_2 = -0.013$ nm/mm, and $d\Delta\lambda_0 = 2.436$ nm, we obtain

$$|d\Delta\lambda - 2.436| = 0.036\Delta D \times 10^{-6} \quad (4')$$

$$\Delta D = 27.778|d\Delta\lambda - 2.436| \times 10^6. \quad (5')$$

Therefore, we can get the displacement from the difference of two FBG wavelength shifts. According to (4') and (5'), we can get the sensor sensitivity of

0.036 nm/mm and the displacement constant of 27.778 mm/nm.

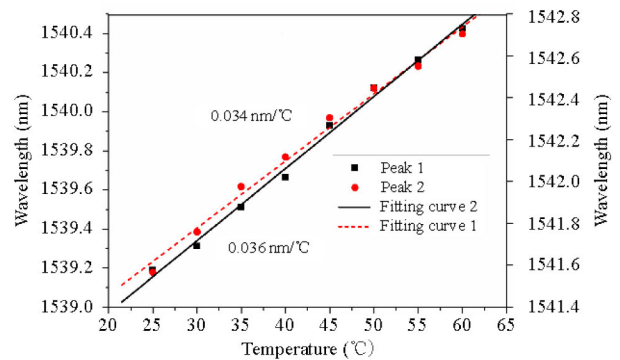


Fig. 5 Responses of dual-wavelength FBG to temperature.

Shen *et al.* [16] proposed fiber -optic displacement sensor based on the reflective intensity modulated technology for the wide range measurement. The sensing range was over 30 cm, which was over 100 times that of the conventional fiber-optic displacement sensor based on the normal single-mode fiber. However, the reliability and stability of the sensor were limited by the fluctuation of the light source and influences of environment. Chen *et al.* [17] proposed a high-sensitivity fiber-optic displacement sensor fabricated by concatenating two core-offset joints with a separation length of 13 mm using a commercial fusion splicer. The displacement sensitivities obtained were up to 0.835 nm/ μ m and 0.227 nm/ μ m in the ranges of 350 μ m to 1000 μ m, respectively. However, it is hard to be used for the large range displacement measurement. As compared, we proposed an FBG displacement sensor with a good tradeoff between the sensitivity and measurement range, which could linearly work in a large measuring displacement range greater than 45 mm with a high sensitivity of 0.036 nm/mm.

To verify the validity of (5'), we chose randomly five testing points, which were (8 mm, 27 °C), (16 mm, 23 °C), (24 mm, 35 °C), (32 mm, 51 °C), and (40 mm, 31 °C). The theoretical curve of the relationship between ΔD and $d\Delta\lambda$ is shown in Fig. 6. Among them, $d\Delta\lambda$ was measured in the experiment.

We then calculated the displacement constant (30.591 mm/nm) which corresponded to the deviation from the theoretical values (27.778 mm/nm) of $\pm 5.063\%$.

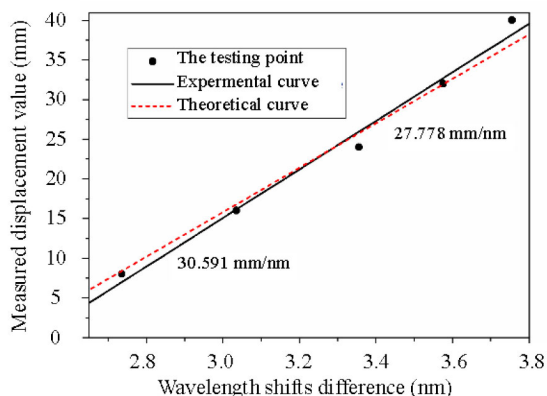


Fig. 6 Relationship between the measured displacement value (ΔD) and wavelength shift difference ($d\Delta\lambda$).

4. Conclusions

In summary, we experimentally demonstrated a self-compensating displacement sensor with the large measuring range. Because it combined the hydramatic structured transducer and FBG into a single sensor system, it possessed the advantages of both types. We demonstrated that it could make linear displacement measurement up to 45 mm with a sensitivity of 0.036 nm/mm. This novel optical fiber displacement sensor has the advantages of the large measuring range, high sensitivity, good durability, and ease to manufacture.

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