Research Article

Study of Three-Component FBG Vibration Sensor for Simultaneous Measurement of Vibration, Temperature, and Verticality

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To achieve simultaneous measurement of measurand vibration, temperature, and verticality, a three-component fiber Bragg grating (TVFBG) vibration sensor is proposed in this paper. Polymer and metal diaphragm sensitization methods are utilized to improve this sensor measurement sensitivity. Project matrix theory is adopted to analyze this sensor. Theoretically, 9×9 nonsingular measuring coefficient matrix of this TVFBG sensor made up by three 3×3 measurand coefficient matrixes is established. In order to effectively extract measurand, Hilbert-Huang transform (HHT) is accepted to process this sensor's center wavelength signals. Calibration experiments are carried out to verify the performance of this TVFBG sensor. Experiment data confirm that this sensor has excellent frequency response and show good linearity at temperature and verticality measurement. Wrist rotation angle measurement experiment is also implemented to further identify this sensor practical value. Through analyzing by HHT, experiment results show that the angle measurement sensitivities of three fiber Bragg gratings which are included in this sensor are separately $25.2 \text{ pm}/^\circ$, $38.2 \text{ pm}/^\circ$, and $38.3 \text{ pm}/^\circ$.

1. Introduction

Simultaneous multiparameter measurement has provided one way which reduces the number of measuring sensors and cuts down detection cost to monitor the health status of engineering structure. Based on the characteristics of fiber Bragg grating (FBG), such as high accuracy, small size, immunity to electromagnetic interference, and multiplexing capacity, FBG sensors have been widely used in aerospace, energy industry, transportation, and geotechnical and civil engineering [1–8]. During the latest decades, there are many works about isochronous multiparameter measurement by FBG sensors have been down. Rao et al. [9] performed the simultaneous measurement of static strain, temperature, and vibration using a multiplexed in-FBG/fibre-F-P sensor. Zhang et al. [10] demonstrated an integrated inline microfiber sensor based on fiber Bragg gratings to simultaneously measure vibration and temperature information for state estimation of cable-stayed bridges.

Based on available research results, a three-component FBG vibration (TVFBG) sensor for synchronous measurement of vibration, temperature, and verticality is proposed in this paper. Due to the fact that axial strain sensitive coefficient of bare FBG is only $0.003 \text{ nm}/\text{MPa}$ [11], many methods have been reported to improve its coefficient, such as polymer sensitization [12, 13], metal diaphragm sensitization [14, 15], and some other mechanical structures [1, 16]. Polymer and metal diaphragm sensitization methods are both used to improve measurement sensitivity of this TVFBG sensor.

According to project matrix theory, 9×9 nonsingular measuring coefficient matrix made up by three 3×3 measurand coefficient matrixes is established. All these 3×3 matrixes are deduced from this sensor theoretical model. Three fiber Bragg gratings (TFBGs) are included in this TVFBG sensor as the sensitive elements. All center wavelengths of TFBGs contain the information of vibration, temperature, and verticality. So as to effectively extract the measurand vibration, temperature, and verticality, Hilbert-Huang transform (HHT) is

FIGURE 1: Basic block diagram and prototype of this TVFBG sensor.

used to analyze the dynamic wavelength signals. Calibration experiment is carried out to test this sensor performance and wrist rotation angle measurement experiment further proves its practical value.

Generally speaking, in this sensor polymer and metal diaphragm sensitization methods are used to improve its measuring sensitivity. Theoretical calculation model based on project matrix theory is set up and HHT is utilized to extract and reconstruct the measurand. It realizes three-parameter measurement at the same time. Due to calibration and wrist rotation measurement experiment results, this TVFBG sensor possesses great potential in engineering application.

2. Structure of the TVFBG Sensor

Basic metal transfer structure and prototype of this TVFBG sensor are shown in Figure 1. This TVFBG sensor is composed of three sensing elements and one metal transfer structure. All these three sensing elements are equidistant distributed around the axial direction and the angle interval is 120° in the circumferential distribution. The sensing element which is shown in Figure 1(c) includes two connection terminals, one spring as the elastic element and one fiber Bragg grating as sensitive element.

Metal transfer structure shown in Figure 1(a) is made up by three link rods, upper fixed and lower free rings. Link rod exhibited in Figure 1(d) is composed of two omnidirectional wheels distributed at both ends and the middle elastic element. Basic geometric parameters of this metal transfer structure are presented in Table 1.

3. Signal Analysis and Measurand Identification

Due to the advantages unlimited by fixed wavelet and adaptive signal processing, HHT [13, 17] is widely adopted as a powerful tool to deal with nonlinear and nonstationary signals. HHT is utilized to pick out three different signals

TABLE 1: Basic geometric parameters of metal transfer structure (unit: mm).

	Length	Height	Outer radius	Inner radius
The ring		7	110	70
Link rod	155		4	
Omnidirectional wheel			5	
Elastomer in the middle of link rod	2.5		5	4

$\Delta\lambda_{iV}$, $\Delta\lambda_{iT}$, and $\Delta\lambda_{iP}$ ($i = 1, 2, 3$) from the original center wavelengths λ_{FBGi} ($i = 1, 2, 3$). $\Delta\lambda_{iV}$, $\Delta\lambda_{iT}$, and $\Delta\lambda_{iP}$ are wavelength changes caused by external vibration, temperature, and verticality angle. Through analyzing by HHT, the original signals could be expressed as

$$\begin{aligned}
 \lambda_{FBG1} &= \lambda_{10} + \sum_{i=1}^n c_{1i}, \\
 \lambda_{FBG2} &= \lambda_{20} + \sum_{i=1}^n c_{2i}, \\
 \lambda_{FBG3} &= \lambda_{30} + \sum_{i=1}^n c_{3i},
 \end{aligned} \tag{1}$$

where λ_{i0} ($i = 1, 2, 3$) and c_{mi} ($m = 1, 2, 3$) stand for residual signals and intrinsic mode functions of the original signals.

3.1. Vibration Identification. Because of middle elastic element, the external vibration signal induces axial dynamic strain on these TFBGs and further leads to the center wavelength changes. Relationship between axial strain ε and center wavelength shift $\Delta\lambda$ could be expressed as

$$\frac{\Delta\lambda}{\lambda} = (1 - p_e)\varepsilon, \tag{2}$$

FIGURE 2: (a) The fixed ring parallels the ground plane. (b) Verticality angle α between the fixed ring and the ground plane.

where p_e is the elastic-optic coefficient of optical fiber and its theoretical value equals 0.22. So, the efficiency of dynamic stress F worked on the optical fiber could be expressed as

$$F = E\varepsilon = k_e \cdot V(t), \quad (3)$$

where E is elasticity modulus of optical fiber, k_e is the elastic coefficient of elastomer in the link rob, and $V(t)$ represents the exterior dynamic signal.

Through (2) and (3), we could get that

$$\begin{aligned} \Delta\lambda_{1V} &= \frac{(1-p_e)}{E} \cdot \lambda_{10} \cdot k_{e1} \cdot V_1(t), \\ \Delta\lambda_{2V} &= \frac{(1-p_e)}{E} \cdot \lambda_{20} \cdot k_{e2} \cdot V_2(t), \\ \Delta\lambda_{3V} &= \frac{(1-p_e)}{E} \cdot \lambda_{30} \cdot k_{e3} \cdot V_3(t) \quad \text{or} \end{aligned} \quad (4)$$

$$\begin{bmatrix} \Delta\lambda_{1V} \\ \Delta\lambda_{2V} \\ \Delta\lambda_{3V} \end{bmatrix} = \mathbf{V} \cdot \begin{bmatrix} V_1(t) \\ V_2(t) \\ V_3(t) \end{bmatrix},$$

where $V_1(t)$, $V_2(t)$, and $V_3(t)$ are exterior vibration signals and $\mathbf{V}$ represents the vibration coefficient matrix.

3.2. Temperature Identification. Temperature changes can be obtained by

$$\begin{aligned} \Delta\lambda_{1T} &= \lambda_{10} \cdot (\alpha + \xi) \cdot T_1(t), \\ \Delta\lambda_{2T} &= \lambda_{20} \cdot (\alpha + \xi) \cdot T_2(t), \\ \Delta\lambda_{3T} &= \lambda_{30} \cdot (\alpha + \xi) \cdot T_3(t) \quad \text{or} \end{aligned} \quad (5)$$

$$\begin{bmatrix} \Delta\lambda_{1T} \\ \Delta\lambda_{2T} \\ \Delta\lambda_{3T} \end{bmatrix} = \mathbf{T} \cdot \begin{bmatrix} T_1(t) \\ T_2(t) \\ T_3(t) \end{bmatrix},$$

where α is thermal expansion coefficient, ξ is thermo-optic coefficient of FBG, $T_1(t)$, $T_2(t)$, and $T_3(t)$ are the measured temperature, and $\mathbf{T}$ is the coefficient matrix of temperature.

3.3. Verticality Identification. While connecting line between upper and lower ring center points is not parallel with geodetic vertical line, the free ring could ceaselessly wiggle until the connecting line parallels the geodetic vertical line based on the function of omnidirectional wheel. The angle between geodetic vertical line and axis of this sensor metal transfer structure is selected as vertical evaluation standard and named as verticality angle α . When this sensor position changes from Figures 2(a) to 2(b), verticality angle α is generated by gravity.

Adding the Cartesian coordinate system to this sensor and assuming that the link rod with FBG1 is vertical orthogonal with x -axis, verticality calculation model is shown in Figure 3.

So, the length changes ΔL_i ($i = 1, 2, 3$) of three link rods are expressed as

$$\begin{aligned} \Delta L_1 &= r(1 + \cos\theta) \cdot \sin\alpha, \\ \Delta L_2 &= r \left[1 - \cos\left(\frac{\pi}{3} + \theta\right) \right] \cdot \sin\alpha, \\ \Delta L_3 &= r \left[1 - \cos\left(\frac{\pi}{3} - \theta\right) \right] \cdot \sin\alpha, \end{aligned} \quad (6)$$

where r is radius of the upper fixed ring and θ is the directional angle between radius line ① and x axis in the XY plane.

Based on the above analysis, verticality calculation formula is expressed as

$$\begin{aligned} \Delta\lambda_{1v} &= \lambda_{10} \cdot (1-p_e) \cdot r(1 + \cos\theta) \cdot \frac{\sin\alpha}{h}, \\ \Delta\lambda_{2v} &= \lambda_{20} \cdot (1-p_e) \cdot r \left[1 - \cos\left(\frac{\pi}{3} + \theta\right) \right] \cdot \frac{\sin\alpha}{h}, \\ \Delta\lambda_{3v} &= \lambda_{30} \cdot (1-p_e) \cdot r \left[1 - \cos\left(\frac{\pi}{3} - \theta\right) \right] \cdot \frac{\sin\alpha}{h} \quad \text{or} \end{aligned}$$

$$\begin{bmatrix} \Delta\lambda_{1v} \\ \Delta\lambda_{2v} \\ \Delta\lambda_{3v} \end{bmatrix} = \mathbf{V} \cdot \begin{bmatrix} P_1(t) \\ P_2(t) \\ P_3(t) \end{bmatrix}, \quad (7)$$

FIGURE 3: Verticality calculation model of this sensor.

where h is height of this sensor and $\mathbf{V}$ is the verticality coefficient matrix. Through (7), verticality angle α and directional angle θ are obtained.

The measurand identification could be concluded in four steps.

- (1) Use HHT to extract different signals $\Delta\lambda_{iV}$, $\Delta\lambda_{iT}$, and $\Delta\lambda_{iP}$ ($i = 1, 2, 3$) from the center wavelengths λ_{FBGi} ($i = 1, 2, 3$).
- (2) External dynamic signals $V_1(t)$, $V_2(t)$, and $V_3(t)$ are obtained by bringing $\Delta\lambda_{iV}$ ($i = 1, 2, 3$) to (4).
- (3) Environment temperatures $T_1(t)$, $T_2(t)$, and $T_3(t)$ are picked out by bringing $\Delta\lambda_{iT}$ ($i = 1, 2, 3$) to (5).
- (4) Verticality angle α and directional angle θ are calculated by bringing $\Delta\lambda_{iP}$ ($i = 1, 2, 3$) to (7).

Therefore, the relationship between center wavelength changes and measurand could be expressed as

$$\begin{bmatrix} \Delta\lambda_{\text{FBG1}} \\ \Delta\lambda_{\text{FBG2}} \\ \Delta\lambda_{\text{FBG3}} \end{bmatrix} \xrightarrow{\text{HHT}} \begin{bmatrix} \Delta\lambda_{1V} \\ \Delta\lambda_{2V} \\ \Delta\lambda_{3V} \\ \Delta\lambda_{1T} \\ \Delta\lambda_{2T} \\ \Delta\lambda_{3T} \\ \Delta\lambda_{1P} \\ \Delta\lambda_{2P} \\ \Delta\lambda_{3P} \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{V} & & \\ & \mathbf{T} & \\ & & \mathbf{P} \end{bmatrix} \begin{bmatrix} V_1(t) \\ V_2(t) \\ V_3(t) \\ T_1(t) \\ T_2(t) \\ T_3(t) \\ P_1(t) \\ P_2(t) \\ P_3(t) \end{bmatrix}. \quad (8)$$

4. Calibration Experiment

For testing the performance of this TVFBG sensor, frequency response, temperature sensitivity, and verticality measuring experiment are all carried out. The basic instruments in these experiments are ASE broadband flattened light source, optical fiber circulator, and sense 20/20. Sense 20/20 is produced by Bay Spec, Inc., and acts as fiber dynamic demodulation instrument. Some other auxiliary equipment such as INV1601 vibration platform produced by Beijing Dongfang Vibration and Noise Technology Research Institute, thermostatic water tank, and protractor are also used in these experiments. The initial center wavelengths of FBG1, FBG2, and FBG3 are 1540.5533 nm, 1534.4096 nm, and 1530.7497 nm.

4.1. Frequency Response Experiment. Figure 4 shows diagram and basic instruments of frequency response experiment which is set up to simulate the exterior vibration environment. This sensor is adhered together with vibration platform through epoxy resin. Its status is kept vertical. In order to improve coupling coefficient, a thin layer ethyl α -cyanoacrylate is coated at the surface of simply supported

FIGURE 4: Frequency response experiment platform.

beam. Detection frequency ranges of sense 20/20 are 0–5 KHz and its frequency demodulation precision is 1 Hz. JZ-1 type vibration source included in the INV1601 vibration platform generates a series frequency from 100 Hz to 1 KHz in steps of 100 Hz with precision 0.1 Hz. The output amplitude is kept at 1.3 m/s^2 in the whole experiment. Comparative analysis data between detected data by this TVFBG sensor and generated data by JZ-1 are utilized as reference indicator to evaluate this sensor frequency response.

4.2. Temperature Sensitivity Experiment. Thermostatic water tank is utilized to change this sensor environment temperature. Diagram of temperature sensitivity experiment is shown in Figure 5. So as to avoid that the center wavelengths of TFBGs are influenced by exterior strain, this TVFBG sensor is statically placed at the bottom of the tank. SM125 (demodulation ranges 1510–1590 nm, demodulation precision 1 pm) is chosen as fiber interrogator. In this whole process, temperature variation ranges are 20°C – 60°C and its step interval is 5°C . Water temperature is also measured by thermal resistance which is selected as contrastive data with this TVFBG sensor. Water temperature is remaining stable for almost one minute at each step. The heating and cooling processes are repeated twice.

4.3. Verticality Measuring Experiment. Protractor which is used in teaching acts as measure verticality angle measuring instrument and its precision is 1° . Instruments used in this experiment are shown in Figure 6. Achieving the purpose that data processing is more convenient, the axis of FBG1 is kept vertical orthogonal with zero depicting line at the beginning of this experiment. The manually controlled FBG1 axis rotates counterclockwise to change the verticality angle α . Due to metal transfer structure, center wavelength of FBG2 is increased and these other two wavelengths are both decreased. Limited by the theoretical maximum strain value of FBG which is $7860 \mu\epsilon$, small ranges verticality measuring experiment is carried out. The manually controlled verticality angle α increases from 0° to 5° with step interval 1° .

5. Data Analysis and Results

Analyzing the experiment data acquired in previous calibration experiment, the basic characteristics of the TVFBG sensor are identified in this section.

FIGURE 5: Diagram of temperature sensitivity experiment platform.

FIGURE 6: Instruments in the verticality response experiment.

5.1. Frequency Characteristic Analysis. Limited by length of this paper, Figure 7 just displays parts of sectional graphs of the demodulation software interface and the controller signals generated by JZ-1. These sectional graphs just display the frequency signals detected by FBG1.

Fast Fourier transform (FFT) is selected to extract frequency information of this TVFBG sensor in the frequency response experiment. The detected frequency data are shown in Table 2.

Formula of relative measuring error is expressed as

$$\delta_F = \frac{(F_{\text{FBGi}} - F_{\text{VS}})}{F_{\text{VS}}} \cdot 100\%, \quad (9)$$

(a) 100 Hz

(b) 500 Hz

(c) 1000 Hz

FIGURE 7: Left: front panel of vibration source controller. Right: demodulation software interface sectional graphs.

TABLE 2: Detected frequency data by this TVFBG sensor.

Generated frequency/Hz	Detected frequency/Hz		
	FBG1	FBG2	FBG3
100	100.4028	100.4028	100.4028
200	200.8057	200.8057	200.8057
300	301.2085	301.2085	301.2085
400	401.3062	401.6113	401.3062
500	502.0142	502.0142	502.0142
600	602.417	602.417	602.417
700	702.8198	702.8198	702.8198
800	803.2227	803.2227	803.2227
900	903.6255	903.6255	903.6255
1000	1004.0283	1004.0283	1004.0283

where F_{FBGi} ($i = 1, 2, 3$) and F_{VS} represent detected frequency and the generated frequency, respectively.

Calculating the measuring error between generated and detected frequency through (9), its ranges are from 0.327% to 0.403%. Such data effectively prove that this TVFBG sensor has excellent frequency response.

5.2. Temperature Sensitivity Analysis. Data in the first heating process are displayed in Table 3 and Figure 8 shows changes of center wavelengths following the temperature variations in the whole temperature sensitivity experiment.

Figure 8 exhibits the fact that the relationship between temperature and center wavelengths has excellent linearity and reproducibility. Temperature sensitivities of FBG1 analyzed by least squares method are $0.0114 \text{ pm}/^\circ\text{C}$, $0.0113 \text{ pm}/^\circ\text{C}$, $0.0113 \text{ pm}/^\circ\text{C}$, and $0.0113 \text{ pm}/^\circ\text{C}$ in the twice heating and cooling processes. Average value of these four sensitivities is selected as temperature sensitivity of FBG1 and its value is $11.3 \text{ pm}/^\circ\text{C}$. Similarly, temperature sensitivities of FBG2 and FBG3 are $13.4 \text{ pm}/^\circ\text{C}$ and $11.2 \text{ pm}/^\circ\text{C}$. Temperature sensitivities of TFBGs are all approximated to the bare FBG. Therefore, this sensor realizes precise temperature measurement.

FIGURE 8: Fitting curves between center wavelengths and temperature.

TABLE 3: Experiment data in first heating procedure.

Temperature/°C	Center wavelength of FBG/nm		
	FBG1	FBG2	FBG3
20	1540.400517	1534.314647	1530.703881
25	1540.553308	1534.40965	1530.749724
30	1540.609982	1534.470089	1530.804002
35	1540.666616	1534.529987	1530.860776
40	1540.724015	1534.593595	1530.918992
45	1540.780719	1534.657476	1530.979152
50	1540.838631	1534.72566	1531.039742
55	1540.897591	1534.797819	1531.100086
60	1540.952174	1534.864976	1531.129372

TABLE 4: Data of verticality measuring experiment.

Angle α /°	Center wavelength of FBG/nm		
	FBG1	FBG2	FBG3
0	1540.0843	1535.2864	1530.4722
1	1540.0578	1535.336	1530.4356
2	1540.0352	1535.3691	1530.3994
3	1540.0033	1535.4215	1530.3658
4	1539.9825	1535.4581	1530.3223
5	1539.9491	1535.4874	1530.2847

5.3. *Verticality Measuring Analysis.* Table 4 gives the center wavelengths of this TVFBG sensor in the verticality measuring experiment.

Fitting curves between wavelength λ_B and verticality angle α are $\lambda_{\text{FBG1}} = -0.0267\alpha + 1540.3$ ($R^2 = 0.9969$),

$\lambda_{\text{FBG2}} = 0.0407\alpha + 1535.3$ ($R^2 = 0.9935$), and $\lambda_{\text{FBG3}} = -0.0375\alpha + 1530.5$ ($R^2 = 0.9988$). Due to the fact that the verticality angle α is very small, its sine value equals itself. Relationship between λ_B and α presents excellent linearity and the verticality measuring sensitivities are 26.7 pm/°, 40.7 pm/°, and 37.5 pm/° severally. All these verticality coefficients are available just under calibration experiment conditions. So, this TVFBG sensor realizes verticality measuring

FIGURE 9: Sample data analyzed by HHT.

and shows excellent measuring linearity at small verticality angle ranges.

6. Wrist Rotation Angle Measurement Experiment

So as to verify the practical value of this TVEBG sensor, wrist rotation angle measurement experiment is implemented. Wrist rotation angle changes from -10° to 10° with step interval of 5° under the same condition in verticality measuring experiment. Sense 20/20 is chosen as the dynamic fiber interrogator. Wavelength data of FBG1 corresponding to angle 0° are selected as sample data to explain signal processing. The sample data processed by HHT is shown in Figure 9.

After HHT analysis, trend signals are chosen as the corresponding verticality angle data. Using the same signal processing methods, the extracted data are shown in Table 5.

Least squares method is used to acquire verticality measuring sensitivities and these values corresponding to TFBGs are $25.2 \text{ pm}/^\circ$, $38.2 \text{ pm}/^\circ$, and $38.3 \text{ pm}/^\circ$ separately. Hence, this sensor can be used in practical measurement.

7. Conclusion

A three-component FBG vibration sensor which could simultaneously measure vibration, temperature, and verticality is realized in this paper. Project matrix theory is chosen as basic theory to establish this sensor theatrical calculation model. HHT is used to analyze this sensor's wavelength signals and reconstruct measurand. Calibration experiments consisting of frequency response, temperature sensitivity, and verticality measuring experiment are carried out. Calibration experiments data confirm that this sensor could realize frequency, temperature, and verticality measurements with

TABLE 5: Extracted center wavelength data analyzed by HHT.

Wrist rotation angle $\alpha/^\circ$	Center wavelength of FBG/nm		
	FBG1	FBG2	FBG3
-10	1540.31	1534.899	1530.858
-5	1540.2125	1535.0854	1530.6487
0	1540.0843	1535.2864	1530.4722
5	1539.9491	1535.4874	1530.2847
10	1539.8126	1535.653	1530.082

high precision. This TVFBG sensor's frequency measuring errors at ranges of 100–1000 Hz are all less than 1% and its temperature and verticality measuring sensitivities are $11.3 \text{ pm}/^\circ\text{C}$, $13.4 \text{ pm}/^\circ\text{C}$, $11.2 \text{ pm}/^\circ\text{C}$, $26.7 \text{ pm}/^\circ$, $40.7 \text{ pm}/^\circ$, and $37.5 \text{ pm}/^\circ$. In order to further verify this sensor practical value, wrist rotation angle experiment is also implemented. Wrist rotation experiment results show that this sensor realizes wrist angle measuring and its sensitivities are $25.2 \text{ pm}/^\circ$, $38.2 \text{ pm}/^\circ$, and $38.3 \text{ pm}/^\circ$. All these experiment data prove that this sensor has certain practical value in engineering.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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