Acceleration sensor of medium-high frequency dual FBG based on L-shaped support sensitization structure

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Abstract

It is a key part for micro seismic crack detection, mechanical equipment operation state and structural health monitoring to measure high frequency vibration. A kind of FBG acceleration sensor based on flexure hinge is proposed targeting at the problem of existing medium-high-frequency FBG acceleration sensor's low sensitivity. Two FBGs are fixed on L-shaped support in a differential arrangement to improve sensitivity of sensor and eliminate adverse effects caused by temperature changes. Matlab and ANSYS software are used to simulate, analyze and optimize sensor. According to the simulation results, the real sensor is made, and the sensor calibration experiment is carried out. Research results show that resonant frequency of sensor is about 1700 Hz and has good linearity in flat range of 50–1000 Hz. Sensitivity of sensor can reach 18.9 pm/g, while linearity is higher than 99%, and temperature sensitivity is merely 0.074 pm/°C. Research results provide reference for researching and developing the same type of sensor, and further improving optical fiber acceleration sensor sensitivity.

Keywords

FBG, acceleration sensor, flexure hinge, medium-high frequency

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Introduction

Pickup and measurement of vibration signal is one of basic and important research directions in fields of micro seismic crack detection, mechanical equipment operation status and structural health monitoring, among which medium-high-frequency vibration signal contains important fault information. It can timely grasp real-time status of equipment, environment and engineering through real-time monitoring of medium-high-frequency vibration signal, effectively avoiding safety accidents.\textsuperscript{1–3} Acceleration sensor is key equipment for monitoring object vibration. Traditional acceleration sensor is mainly piezoelectric, resistive and capacitive,\textsuperscript{4,5} which has advantages of low cost and mature technology. But, electrical acceleration sensor is vulnerable to external magnetic field interference, complicated wiring, serious attenuation when transmitting signals over a long distance and other shortcomings.\textsuperscript{6,7} As a special kind of optical fiber sensing element, Fiber Bragg Grating (FBG) has advantages of anti-electromagnetic interference, anti-optical power fluctuation, small volume and light weight. It serves as a compensation for shortcomings of electrical acceleration sensors in field of medium-high-frequency vibration measurement.\textsuperscript{8–10}

FBG acceleration sensor is a branch of FBG sensor that has made great progress in recent years.\textsuperscript{11} Yongxing Guo et al.\textsuperscript{12} designed a new accelerometer, whose mass block is welded with metal coated optical fiber, and both ends of optical fiber fixed on shell. Natural frequency of sensor is 3600 Hz and sensitivity is only 1.7 pm/g. Wang et al.\textsuperscript{13} proposed a kind of Fiber Bragg Grating acceleration sensor with elastic steel pipe structure, which has good linear response at

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0–1200 Hz and sensitivity can reach 4.01 pm/g. Zhu et al.\(^{14}\) proposed a double Fiber Bragg Grating acceleration sensor with lantern shaped metal shell. Such sensor has strong anti-transverse interference capability, its resonant frequency is about 1175 Hz and its sensitivity is 9.4 pm/g. Dai et al.\(^{15}\) designed a double hinge accelerometer with a resonant frequency of about 3000 Hz, which can be used for medium and high frequency measurement. Bottleneck of low sensitivity of FBG acceleration sensor in measuring medium-high-frequency vibration still exists although frequency range that can be measured by medium-high-frequency FBG acceleration sensor is gradually improved in past research results.

An FBG acceleration sensor based on flexure hinge is proposed targeting low sensitivity of existing FBG acceleration sensor in measuring medium-high-frequency vibration. Such sensor is designed as a whole to reduce mechanical fatigue and friction loss that may occur during assembly of various parts. Two FBGs are symmetrically pasted between mass block and L-shaped support by two-point pasting method to weaken influence of temperature on sensor, and differential operation is used to improve sensitivity of sensor. The theoretical model of the accelerometer is established, and the working principle is theoretically deduced. Influence of structural parameters on sensitivity and resonant frequency of sensor is analyzed by Matlab software. Dynamic characteristics of sensor are analyzed by finite element method combined with ANSYS software, and the sensor samples are produced. Experiments are carried out to test the dynamic property of the fabricated sensor samples.

**Sensor design**

**Sensor structure**

Sensor structure contains base, flexure hinge, mass block and L-shaped support. Such sensor adopts an integrated design and is made of complete spring steel through wire cutting and heat treatment. So there will be no mechanical friction in practical working conditions, and performance of sensor can be fully exerted to the greatest extent. The two same FBGs are pasted in optical fiber groove of mass block and L-shaped support with UV glue. FBG is prestressed in pasting to prevent chirp effect. Specific structure is shown in Figure 1. As shown in Figure 1 that L-shaped bracket medium-high-frequency dual FBG acceleration sensor takes FBG as sensing element to convert object high-frequency vibration signal into FBG center wavelength offset signal. Mass block rotates slightly around center of flexure hinge under action of inertial force when sensor detects vibration signal, mass block vibrates slightly around hinge, and fiber fixing point moves from Point B to Point B. Length of fiber grating AB at this time is \(l_1\), rotation angle is \(\alpha\), length of fiber grating AB is \(l_2\), rotation angle is \(\beta\), and length of BB is \(\Delta x\). According to the cosine theorem that

\[
l_1' = \sqrt{\Delta x^2 + l_1'^2 - 2l_1\Delta x \cos \alpha} \quad (1)
\]

\[
l_2' = \sqrt{\Delta x^2 + l_2'^2 - 2l_2\Delta x \cos \beta} \quad (2)
\]

Then stretching amount of Fiber Bragg Grating

\[
\Delta l_1 = l_1 - l_1' = l_1 - \sqrt{\Delta x^2 + l_1'^2 - 2l_1\Delta x \cos \alpha} \quad (3)
\]

\[
\Delta l_2 = l_2 - l_2' = l_2 - \sqrt{\Delta x^2 + l_2'^2 - 2l_2\Delta x \cos \beta} \quad (4)
\]

With conditions where sensor signal is a micro amplitude vibration signal, \(\beta < \alpha\) and \(l_1 = l_2\), sensor sensitization effect is realized, which makes axial tension of Fiber Bragg Grating consistent with vibration direction of external excitation signal, and can effectively increase change amount of central wavelength of Fiber Bragg Grating, so as to improve the sensitivity of the sensor.

**Sensor sensitivity analysis**

Because the vibration amplitude of high-frequency vibration signal is small and decays rapidly, the mechanical analysis of the sensor is carried out. XOY plane of sensor structure is taken as per Figure 1 to...
establish mechanical model, replacing flexure hinge with ideal hinge, regarding mass block as rigid body without deformation, while only considering elastic coefficient of optical fiber and hinge part. And vibration model of sensor is shown in Figure 3.

It can be learnt from Figure 3 that $R$ is radius of flexure hinge, $t$ is thickness of hinge, $e$ is length of mass block, and $h$ is height of mass block. When acceleration excitation signal acts on sensitive direction of sensor, mass rotates slightly around center of flexure hinge under action of inertial force, and system achieves torque balance under action of inertial force, so the following can be made:

$$mad - k\Delta l \frac{h}{2} - K\theta = 0$$  \hspace{1cm} (5)

Where, $m$ is mass of block, $d$ is distance between mass center of mass block and hinge center, $\Delta l$ is stretching distance of optical fiber, $k$ is elastic coefficient of optical fiber, $K$ is hinge rotation stiffness, and $\theta$ is hinge rotation angle.

Sensor sensitivity $S$ is ratio of FBG central wavelength change to acceleration, that is, sensitivity $S$ of FBG acceleration sensor is ratio of grating central wavelength change to acceleration $a$, that is:

$$S = 2 \cdot \frac{\Delta \lambda}{a} = \frac{2(1 - P_e) \lambda_{BC}}{a} = \frac{2(1 - P_e) \lambda_{B}}{l} \frac{md}{kh/2 + 2K/h}$$  \hspace{1cm} (6)

Where, $P_e$ is elastic optic coefficient. $\lambda_{B}$ is central wavelength of FBG. $\epsilon$ is optical fiber strain. Mass block’s center of gravity $d = R + e/2$, $e$ is length of mass block. $R$ is radius of straight circular hinge. Sensitivity referred to in this paper is sensitivity obtained by differential operation of two FBG central wavelengths, which is $2S$.

In equation (6) that sensitivity is not only restricted by size of sensor, but also affected by hinge stiffness, so hinge stiffness $K$ is

$$K = \frac{EtR^2}{12} \left[ \frac{2s^2(6s^2 + 4s + 1)}{(2s + 1)(4s + 1)} + \frac{2s^4(2s + 1)}{(4s + 1)^{3/2}} \arctan \sqrt{4s + 1} \right]$$  \hspace{1cm} (7)

Where $E$ is elastic modulus of material, and $t$ is thickness of hinge, $s = R/t$. 

**Figure 1.** Schematic diagram of sensor structure.

**Figure 2.** Schematic diagram of FBG stretching amount amplification.

**Figure 3.** Sensor vibration model.
Sensor resonance frequency analysis

Resonance frequency is another important parameter of acceleration sensor. When external resonant frequency reaches resonance frequency of sensor, sensor will resonate with vibrating object, and amplitude increases sharply. So, the higher the resonant frequency, the wider the available frequency band of sensor, and the more high-frequency signals can be measured. Supposing inertia moment of mass rotating around hinge center is \( J \), and resonant frequency \( f \) of the whole system is obtained through dynamic equation

\[
 f = \frac{1}{2\pi} \sqrt{\frac{2k(h/2)^2 + K}{J}}
\]

Where inertia moment \( J \) is

\[
 J = m\frac{e^2 + h^2}{12} + md^2
\]

Impact analysis of structural parameters

Influence of structural parameters on sensors

Vibration characteristics and measurement range of sensor have something to do with resonant frequency of sensor. It is necessary to optimize design to increase sensor sensitivity \( S \) as much as possible and take an appropriate value for resonant frequency \( f \) in order to obtain higher sensitivity in a higher resonant frequency range. From results of theoretical analysis, it can be seen that length \( e \), height \( h \) and hinge thickness \( t \) of mass block are key parameters affecting sensor sensitivity \( S \) and resonant frequency \( f \). So, structural parameters of sensor are analyzed in case other parameters have been determined. When excitation acceleration is \( 1g \), Matlab software is used to analyze key parameters of sensor, such as length \( e \) of inertial mass block, height \( h \) of inertial mass block and thickness \( t \) of hinge. Cutting radius \( R \) of hinge is set to 3 mm. Since the designed sensor aims to measure medium and high frequency vibration and requires integrated processing, the elastic modulus of the processing sensor material should be large enough. Therefore, 65 Mn spring steel is selected to process the sensor, its elastic modulus is 190 GPa, density is 7850 kg/m\(^3\), thickness of sensor is 15 mm, and cross-sectional area of optical fiber is \( 1.23 \times 10^{-8} \) m\(^2\), elastic modulus is 72 GPa, effective elastic-optical coefficient is 0.22, central wavelength of grating is 1550 nm, and \( l \) is 5 mm.

First of all, influence of mass block length \( e \) on sensor sensitivity and resonant frequency is analyzed, supposing \( t = 2 \) mm, \( h = 5 \) mm, \( 1 \) mm \( \leq e \leq 10 \) mm. The above parameters and equations (6) and (8) are brought into Matlab Program, and results are shown in Figure 4.

It can be learnt from Figure 4 that sensor sensitivity \( S \) increases with increase of length \( e \) of mass block, and resonant frequency \( f \) decreases with increase of length \( e \) of mass block. When \( 1 \) mm \( < e < 5 \) mm, resonant frequency \( f \) decreases rapidly with increase of \( e \), and change is gradually stable when \( e > 5 \) mm. Considering that design goal of sensor is to collect high-frequency vibration signals and sensitivity should not be too low, mass block length \( e = 5 \) mm is selected.

Secondly, influence of mass block height on sensor sensitivity and resonant frequency is analyzed. At this time, take \( e = 5 \) mm, \( t = 2 \) mm, \( 5 \) mm \( \leq h \leq 10 \) mm. The above parameters and equations (6) and (8) are brought into Matlab Program, and results are shown in Figure 5.

It can be learnt from Figure 5 that sensor sensitivity \( S \) increases with increase of mass block height \( h \), and resonant frequency \( f \) decreases with increase of mass block height \( h \). When \( 5 \) mm \( < h < 7 \) mm, sensitivity \( S \) increases rapidly with increase of, and when \( h > 7 \) mm, change of \( S \) is gradually stable. Resonant frequency \( f \)
changes nearly linearly in the whole process. Mass block height $h = 5$ mm is selected in order to obtain higher resonant frequency.

Finally, influence of hinge thickness $t$ on sensor sensitivity and resonant frequency is analyzed. According to the above results, select $e = 5$ mm, $h = 5$ mm, $0.5$ mm $\leq t \leq 3$ mm, and the above parameters and equations (6) and (8) are brought into Matlab Program, and results are shown in Figure 6.

It can be learnt from Figure 6 that sensor sensitivity $S$ decreases with increase of hinge thickness $t$, and resonant frequency $f$ increases with increase of hinge thickness $t$. When $0.5$ mm $< t < 2$ mm, sensitivity $S$ decreases rapidly with increase of $t$, and when $> 7$ mm, change of $S$ is gradually stable. It is taken as $t = 0.5$ mm, considering limitations of sensor material selection and processing technology.

Multiple groups of data are taken for test and simulation in order to make sensor have wide measurement frequency band and high sensitivity. Optimized parameter results are $t = 0.5$ mm, $e = 5$ mm, $h = 5$ mm, $m = 2.94375$ g. Putting the obtained sensor size parameters into formulas (7), (8) and (9), the natural frequency of the sensor is about 1627.5 Hz. Even though theoretical analysis and calculation are simple and concise, theoretical analysis cannot reflect dynamic change of sensor, and there will be a large deviation from actually measured value. So sensor parameters are further simulated and analyzed by using finite element idea and ANSYS software based on theoretical analysis.

### Finite element analysis

To further study dynamic response characteristics of sensor, solid model is firstly established by Solidwork. Secondly, established assembly model is imported into ANSYS Workbench software. And designed sensor is finally analyzed by finite element method. Key parameters of sensor are shown in Table 1.

Fixed constraint is firstly applied to bottom of sensor model, and external load of standard earth gravity acceleration $g$ is applied to the whole sensor. Modal simulation analysis of model is carried out through grid division, and strain cloud diagram of model is obtained, as shown in Figure 7.

As shown in Figure 7(a) that natural frequency of the structure is 1774.8 Hz. According to Figure 7(b) that the second-order natural frequency of sensor is 4848.5 Hz, which is similar to the theoretical analysis.

| Table 1. Structural Parameters of FBG Acceleration Sensor. |
|------------------------------------------------------------|
| Name | Description | Length (mm) |
|------|-------------|-------------|
| $i$  | Mass block width | 15          |
| $h$  | Mass block height | 5           |
| $c$  | Mass block length | 5           |
| $r$  | Hinge radius | 3           |
| $t$  | Hinge thickness | 2           |

![Figure 6. Effect of hinge thickness $t$ on sensor sensitivity and resonant frequency.](image)

![Figure 7. Sensor modal analysis: (a) first order model and (b) second order model.](image)
results, The reason for the small error may be: the division accuracy selected when the sensor is meshed is too rough, which leads to a slight deviation between the final simulation result and the theoretical value. ANSYS simulation results shows difference between the first and second natural frequencies of sensor is large, which shows that cross coupling of sensor is small where cross interference reduction is possible.

Sensor calibration experiment

The FBG used in the sensor is three fiber Bragg gratings in the same batch, whose central wavelength is 1560.5 nm, reflectivity is $\geq 90\%$, and the length of the FBG gate region is 5 mm. The reflection spectrum is shown in Figure 8.

The apparatus for experimental test of the sensor principally included function signal generator, signal amplifier, standard exciter, FBG demodulator, computer, etc. The test was performed with a function signal generator (DG1022) from RIGOL Technologies with a sampling rate of 1 GSa/s, 14 quasi-waveform functions and abundant standard interfaces designed for users to remotely control the data transmission of instruments and USB interfaces via Web. The signal amplifier (MWY-TZQ50) was manufactured by Beijing Weiyun with a frequency response range of 1–15,000 Hz and an SNR of more than 75 dB to work with the function signal generator to amplify the function signals. The FBG demodulator (MWY-FBG-CS800) was also manufactured by Beijing Weiyun, which has 8 signal acquisition channels, each channel can collect optical signals independently, the sampling frequency can reach 1 kHz and a built-in laser source to deliver the transmitted light waves to FBG acceleration sensor on the vibration exciter system via optical fibers; additionally, the FBG demodulator received the FBG reflection spectrum, conducted spectral analysis and data acquisition inside, and transferred the acquired data to the computer in the end. The experimental test system established with above-noted devices for the multi-cantilever beam low-frequency FBG acceleration sensor is shown in Figure 9(b).

Dynamic calibration and performance test are needed to calibrate performance parameters of sensor. Sensor base is fixed on vibration table and kept perpendicular to vibration direction of vibration table. FBG is introduced into two channels of wavelength demodulator, and data is displayed and recorded in real time by computer.

Amplitude frequency response test

Firstly, sine excitation signal with output acceleration value of 5 m/s$^2$ is adjusted by signal generator, and frequency sweep test is carried out for sensor in order to study amplitude frequency characteristics of sensor. Sweep frequency range is selected as 10–2200 Hz and step length is 300 Hz as per simulation results. Approximate range of resonant frequency of sensor is determined, and then step length is taken as 100 Hz for repeated experiments. Then reread sampling is performed in steps of 50 Hz near the peak range. In the

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**Figure 8.** The spectrum of the FBG sensor at room temperature.

**Figure 9.** Sensor calibration experimental system: (a) schematic diagram of vibration experiment system and (b) physical drawing of vibration experiment system.
end, amplitude frequency characteristic curve of sensor is obtained as shown in Figure 10.

It can be learnt from Figure 10 that resonant frequency of sensor is about 1700 Hz and has a relatively flat response at 50–1000 Hz. Experimental value of the first-order frequency of sensor deviates from theoretical value because prestress of optical fiber is not considered in theoretical analysis and finite element simulation, and material properties of actually assembled sensor are different from those in theoretical analysis and finite element.

**Sensitivity coefficient test**

Test points with acceleration higher than 500 Hz are no longer continuous due to limitation of shaking table. Signal generator shall be adjusted so that output frequencies of shaking table are 160, 325, and 495 Hz, so as excitation acceleration value of shaking table with a variation range of 1–14 m/s² and a step size of 1 m/s², in order to obtain sensitivity characteristics of sensor, and data of central wavelengths of the two FBGs is repeatedly recorded. Results are shown in Figure 11.

It can be learnt from Figure 11 that under frequency of 160 Hz, acceleration sensitivity of sensor is 17.50 pm/g, and fitting determination coefficient $R^2 = 0.9970$. Under frequency of 325 Hz, acceleration sensitivity of sensor is 19.56 pm/g, and fitting determination coefficient $R^2 = 0.9982$. Under frequency of 495 Hz, acceleration sensitivity of sensor is 19.82 pm/g, and fitting determination coefficient $R^2 = 0.9986$. To conclude, sensitivity of medium-high-frequency dual FBG acceleration sensor with L-shaped support is about 18.96 pm/g and resonant frequency is about 1700 Hz. It can be used to detect vibration signals within 50–1000 Hz, and its sensitivity is higher than that of other medium-high-frequency FBG acceleration sensors.

**Lateral anti-interference capability**

Characteristic of anti-lateral interference is also an important performance index to be considered for single degree of freedom acceleration sensor. Bottom of sensor is fixed on side of horizontal shaking table in this experiment, so that vibration direction is perpendicular to direction of vibration measuring spindle of sensor in order to study lateral anti-interference characteristics of acceleration sensor. Sinusoidal excitation signal with acceleration of 10 m/s² and frequency of 495 Hz is set. Lateral anti-interference characteristic curve of sensor is obtained by comparing drift of output wavelength with results in direction of vibration measuring spindle, as shown in Figure 12.

It can be learnt from Figure 12 that lateral response and transverse response of sensor are 20.3 pm and 1.8 pm respectively, and wavelength drift of transverse...
response is only 8.87% of lateral response, showing that sensor can be regarded as a single degree of freedom vibration under vibration conditions, and has strong lateral anti-interference capability.

**Self-compensation capability of temperature**

Self-compensation capability of temperature is an important capability for FBG acceleration sensor, which is directly related to working capability of sensor in large temperature difference environment. Sensor is placed in high and low temperature damp heat test chamber (MQ-TH1000F-2N, temperature range $-70^\circ C$ to $+150^\circ C$), and FBG is connected to FBG wavelength demodulator through wiring outlet on outer wall of high and low temperature damp heat test chamber. Oven temperature changes from $-20^\circ C$ to $60^\circ C$ in steps of under $10^\circ C$. It is held for 30 min after each temperature rising to corresponding node of temperature, and FBG center wavelength offset is repeatedly collected at this time node for many times. In the end, temperature change curve of sensor center wavelength is obtained, as shown in Figure 13.

It can be learnt from Figure 13 that temperature sensitivity of single FBG is $16.97 \text{ pm/}^\circ C$, and double FBG temperature sensitivity is $0.074 \text{ pm/}^\circ C$ after differential operation. Double FBG sensitivity to temperature is reduced by about 230 times (57 dB) compared with a single FBG sensor. So sensor has good self-compensation capability of temperature.

**Conclusion**

An FBG acceleration sensor based on flexure hinge is proposed in this paper targeting at the problem of low sensitivity of existing FBG acceleration sensor when measuring medium-high-frequency signals. Two FBGs are fixed on L-shaped support in a differential arrangement to improve sensitivity of sensor and reduce adverse effects of temperature changes. Research results show that resonant frequency of sensor is about $1700 \text{ Hz}$ and has good linearity in flat range of $50$–$1000 \text{ Hz}$. Sensitivity of acceleration sensor can reach $18.9 \text{ pm/g}$, transverse anti-interference degree is less than $8.87\%$, and temperature sensitivity of double FBG after differential operation is only $0.074 \text{ pm/}^\circ C$. As shown in Table 2, Compared with other FBG acceleration sensors, the sensor designed in this paper improves the sensitivity to $18.9 \text{ pm/g}$, further reduces the volume, and has better temperature self-compensation ability, but there is still much room for improvement, such as lateral anti-interference capability. As a result, the original scheme can be further improved and be applied to monitoring research in fields like micro seismic crack detection, mechanical equipment operation state and structural health monitoring as soon as possible.

**Declaration of conflicting interests**

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| Sensor name | Sensitivity (pm/g) | Flat range (Hz) | Frequency (Hz) | temperature sensitivity (pm/°C) |
|-------------|-------------------|----------------|---------------|-------------------------------|
| L-shaped Dual FBG acceleration | 18.9 | 50–1000 | 1700 | 0.074 |
| Welding-packaged accelerometer | 1.7 | 50–1000 | 3600 | N/A |
| Elastic steel pipe structure acceleration | 4.01 | 60–1200 | 3993 | N/A |
| Lantern Shape Metallic Shells acceleration | 9.4 | $\leq 1175$ | 1175 | N/A |
| Integrative matrix acceleration | 12 | 8–2000 | 3000 | N/A |

**Table 2. FBG acceleration sensor performance comparison.**

![Figure 13. Temperature self-compensation characteristics.](image)
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