A Novel Fiber Bragg Grating Accelerometer Based on Fiber Vibrating Wire

Qi Jiang

School of Control Science and Engineering
Shandong University
Jinan, Shandong, China

Minghao Yu ,Xin Zhou, Tengyun Guo, Jinxue Song

School of Control Science and Engineering
Shandong University
Jinan, Shandong, China

Abstract—**A fiber Bragg grating (FBG) accelerometer based on fiber vibrating wire is presented. Finite element analysis has been done and experiments are carried out to demonstrate the performance of this FBG accelerometer. The seismic simulation experimental results indicate that the system has a good response to the 50–400 Hz vibration signal. What more, the accelerometer has a high sensitivity which can reach 108.6 pm/G at 100Hz. The linear responsivity and repeatability are also tested. The responsivity error is less than 2.5% and repeatability error is less than 0.03%. There is an extremely linear relationship between amplitude of detected signal and acceleration.**

Keywords-micro-seismic; fiber Bragg grating; accelerometer

I. INTRODUCTION

Since the first demonstration of permanent gratings in an optical fiber by Hill et al. in 1978 [1, 2], the advantages of fiber Bragg grating (FBG) sensing are well known and have been widely extolled in the research literature [3]. In many applications, the FBG based sensors have shown significant advantages over the conventional electronic sensors, including immunity from electromagnetic interferences, high temperature survivability, corrosion resistance and ability to multiplex. Owing to which the accelerometers based on FBG have made a tremendous progress [4]. Normally, the conversion of the acceleration applied to the sensor into the strain is carried out by a cantilever, to which the sensing FBG is fixed. The acceleration will cause the strain of the cantilever [5, 6, 7], and the FBG will deform with the cantilever because of the inertia mass's vibration. The center wavelength of reflected light will shift with the change of strain acting on the FBG. One year ago, a novel one-degree-of-freedom micro-seismic sensor based on fiber vibrating wire was put forward. The oscillator is penetrated by the optical fiber and mounted near the grating to make a micro-seismic detecting structure [8]. The detection process is without the help of the cantilever beam structure. Because of that, the sensitivity and frequency response range have been enhanced. In this paper, we would farther improve the vibrating wire accelerometer based on FBG. A horizontal fiber has been added to the accelerometer to decrease the cross-sensitivity. What's more, a new detection system was built and farther experiments were done.

II. THE STRUCTURE AND SENSING PRINCIPLE

The sensing function of an FBG derives from the sensitivity of both the refractive index and grating period to the externally applied mechanical or thermal perturbations [9]. The strain field affects the response of an FBG directly, through the expansion and compression of grating pitch size and through the strain-optic effect, that is, the strain-induced modification of the refractive index. The FBG accelerometer proposed in this paper can be simplified to a spring-mass system. With the fiber's spring coefficient given by K=EA/L, the system's natural frequency is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{1}$$

As the Hooke law, if we exert a force F on the fiber along the axial, the shift of centre wavelength $\Delta\lambda_B$ can be formulated:

$$\Delta\lambda_B = \frac{1}{E} \times \frac{F}{S} \times (1-P_e) \times \lambda_B \tag{2}$$

Where P_e is the effective elasto-optical coefficient; $E = F \times L / S \times \Delta L$ is the modulus of elasticity of fiber; S is the cross-sectional area. As the fluctuation of temperature is ignored, the (2) can be transformed to:

$$F = \varepsilon \times \Delta\lambda_B / (1-P_e) \tag{3}$$

ε is a constant which value is $E \times S / \lambda_B$; When the shift of centre wavelength is small enough compared with its original value, we treat P_e as a constant too. Combining (3) and $F = ma$, the acceleration of oscillator is expressed as:

$$a = \varepsilon \times \Delta\lambda_B / (1-P_e) \times \text{m} \tag{4}$$

m is the mass of oscillator. By analyzing (4), we can see that, once fiber is elected, the length of the horizontal and perpendicular optical fiber and the mass of the oscillator will decide the maximal acceleration of accelerometer. If the structure is ready-made, the length of the optical fiber is fixed. Then, we can change the mass to adjust the system's

maximal acceleration. Without considering the effect of temperature, the $\Delta\lambda_B$ change with the stress exert on the FBG. What more, the acceleration is proportional to $\Delta\lambda_B$. So, we can record the shift of centre wavelength to detect the acceleration. Except that, to ensure the vibration's stability, the oscillator we choose must have a regular shape, such as cuboids, ellipsoid [10].

Finite element analysis (FEA) was used to predict the strain distribution on the FBG. The simulation was performed utilizing commercial software ANSYS, as shown in Fig.1. In order to reduce the complexity, ignore the frame construction and apply displacements on the areas which connect fiber and frame. Using the modal analysis in ANSYS 12.0, we find that vibration direction of the sixth mode is vertical. We separate the sixth mode into ten substeps. Fig. 2(a) shows the first substep of it. As shown in the picture, the fiber bear averaged force. We can detect the force by fiber to measure the acceleration of oscillator.
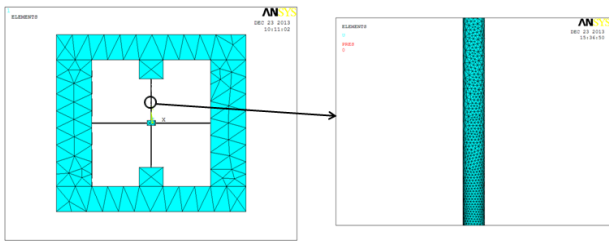

Figure 1.   Finite element analysis model

According to the ANSYS model, a materialized object has been made as shown in Fig. 2(b) and the parameters of this sensor are shown in Talbe.1. A horizontal fiber had been added to the accelerometer to effectively decrease cross-sensitivity. In the assembly process, tighten the zero adjust screws at the beginning and loosen it when the fiber had been fixed on the frame. This structure can make the FBG pre-tensioned quickly and easily. The FBG was positioned on the above of the oscillator. As a result, the FBG can be better tightened because of the oscillator's gravity.
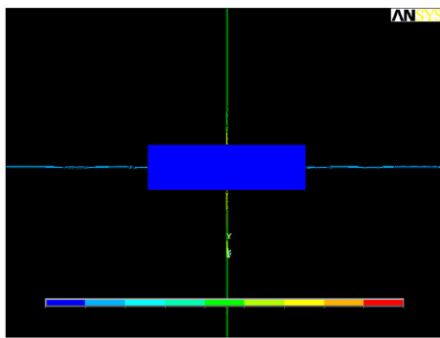
(a)
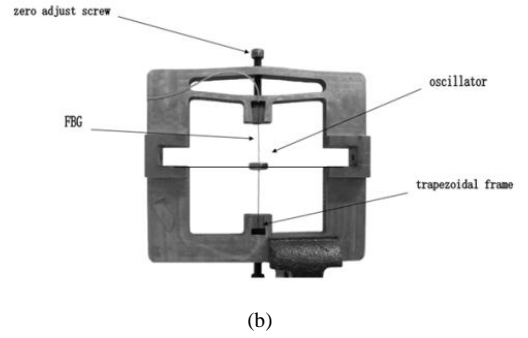
(b)

Figure 2.   (a) transient state of the FBG

(b) the packaged FBG acceleration sensor

TABLE I.   PARAMETERS OF THIS SENSOR

Parameters	Description	Value	Unit
L_1	The length of accelerometer sensor	16	cm
L_2	The width of accelerometer sensor	14	cm
L_3	The length of fiber between structure	6.5	cm
m	The weight of oscillator	4.63	g
L	The length of FBG	1.4	cm

III. THE EXPERIMENTS AND RESULTS

The experimental set up used to test the accelerometer's performance is illustrated in Fig. 3. Signal generated by the generator and sequentially amplified by the power amplifier was used to provide the sinusoidal excitation signal for vibration exciter. Vibration exciter will make the accelerator in sinusoidal vibration which has the same frequency with original signal. A broad-band erbium fiber amplifier source (1.5um, 20-nm spectral width (FWHM), ~21.93-mW) was used to illuminate the FBG through a 2×2 single-mode coupler. The reflected signal was guided back through the 2×2 coupler to the input of a high-speed FBG interrogation unit. BaySpec's FBGA interrogation analyzer which sampling frequency can reach 5 kHz is an integrated spectral engine simultaneously covering multiple wavelengths for precise and rapid fiber Bragg grating (FBG) sensor system measurements. The output signal of the FBG accelerometer was recorded and analyzed in a laptop by an application implemented in the LabVIEW software. A standardized charge acceleration sensor was fixed on the vibration exciter with the FBG accelerometer together to carry out the control experiment. Influence of temperature is ignored because the lab's temperature varies slowly.
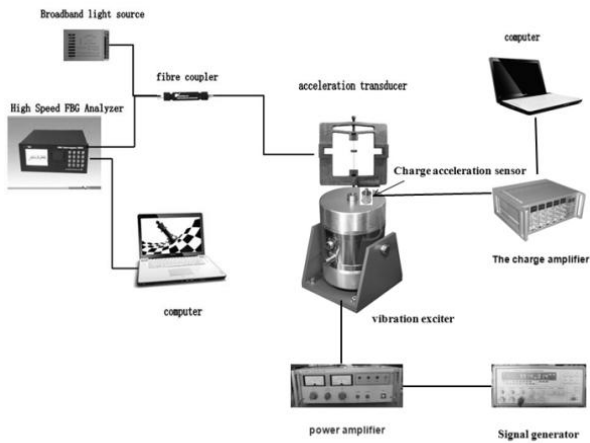
Figure 3.   Vibration experimental system

A   Comparison between the standardized charge acceleration sensor and the FBG sensor

Because the detection signals were obtained through different way, they are out-sync in time domain. However, if the detection time is long enough, they should have a similar performance in frequency domain. In order to make sure the validity of test data, we record of the standardized charge acceleration sensor and the FBG sensor for ten seconds. Select the middle 0.25 seconds as the analytical data. The vibration signals of 50Hz with 0.5G acceleration had been shown in Fig. 4. Because the sampling frequency of standardized charge acceleration sensor is ten times of the FBG sensor, standardized charge acceleration sensor has larger amplitude the FBG sensor. From the frequency spectrum of vibration signal, the both signals have same peak in the frequency and power spectrum.
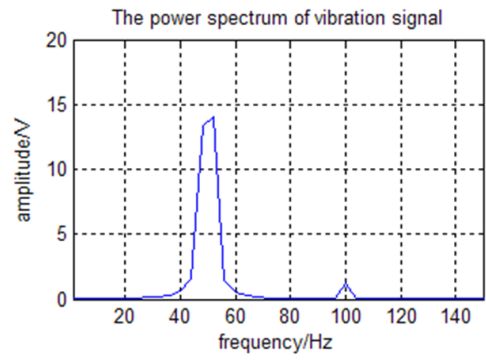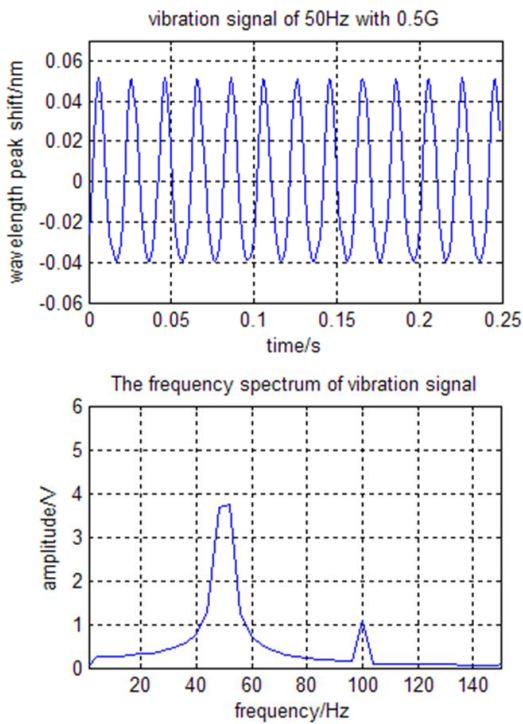
(a)   vibration signal of accelerometer based on FBG
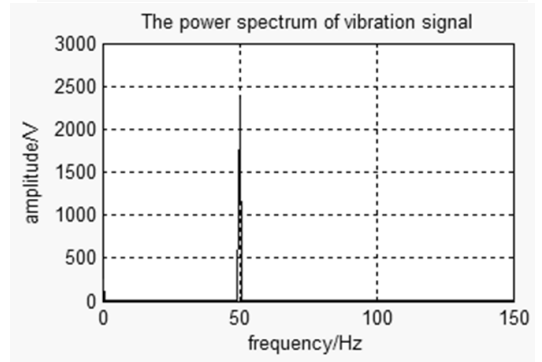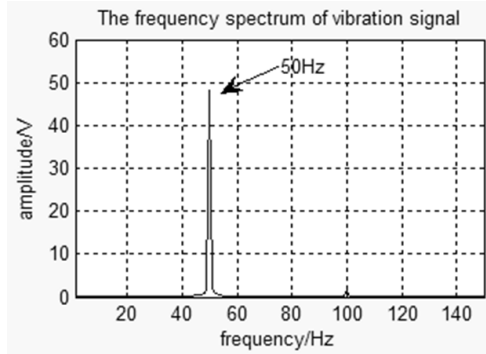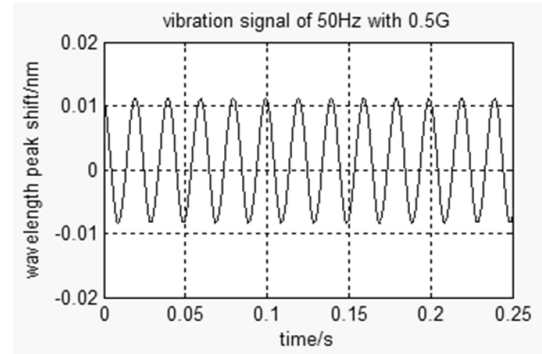
(b)   vibration signal of standardized charge acceleration sensor

Figure 4.   Comparison between the standardized charge acceleration sensor and the FBG sensor

B   Linear responsivity and repeatability

We use the shift of wavelength peak to show the vibration. The experiments show that the offset of peak extremely linear with the signal which we set. The vibration

signal of 50Hz with different acceleration in the time domain is shown in Fig. 5.

There is a linear relationship between the amplitude of wave and the acceleration as shown in Fig. 6, which shows the 50Hz and 100Hz harmonic oscillation output of the FBG accelerometer, with the sensitivity of 78.9 pm/G and 108.6 pm/G respectively. Obviously, the sensitivity increases as the frequency increases. And the calculating data indicate that, the responsivity error is less than 2.5% and repeatability error is less than 0.03%.

In order to demonstrate the accelerometer's repeatability, we recorded the data ten times. In Fig.7, the frequency is 100Hz and 400Hz, when the standardized charge acceleration sensor is remained at 0.2G. Each of contiguous detect times are separated in time by ten seconds. By current experiment, the accelerometer has a good repeatability in range from 50 to 400Hz.
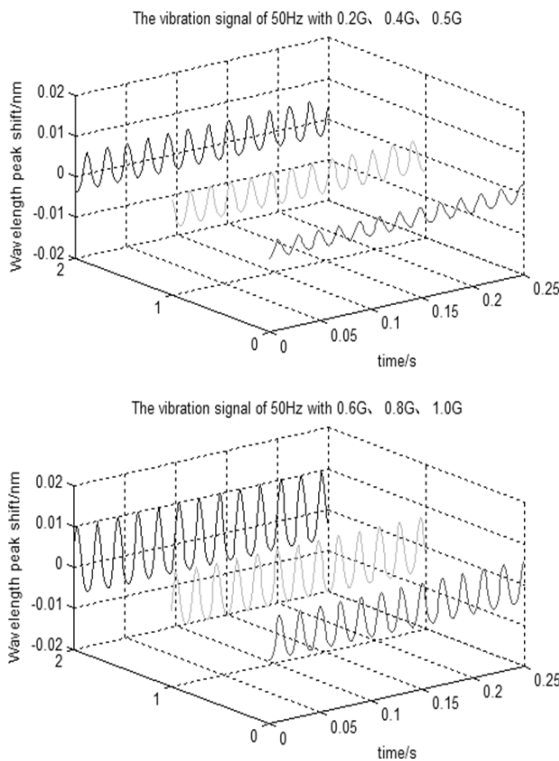

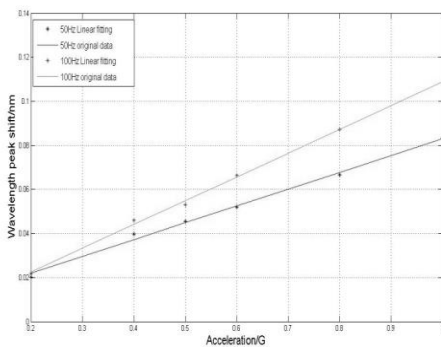Figure 5. the vibration signal of 50Hz with 0.2G, 0.4G, 0.5G, 0.6G, 0.8G and 1.0G

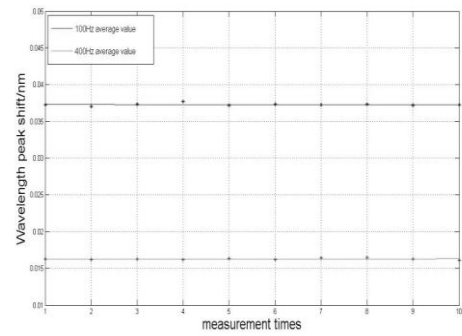Figure 6. the linear fitting of 50 and 100Hz signal

Figure 7. repeatability of different frequency with 0.2G

IV. CONCLUSION

An accelerometer based on fiber vibrating wire is presented. By abandoning the cantilever beam, the accelerometer can be miniaturized easily and get a very high sensitivity at the same time. By adjusting the quality of oscillator, the system's natural frequency can be set at a reasonable range. The horizontal fiber which is added to the accelerometer can effectively decrease the cross-sensitivity. Besides that, we can also add a matched FBG to eliminate the effect of temperature. In the frequency range from 50 to 400Hz, the experimental resonance frequency is almost same with the theoretical resonant frequency. The sensitivity is 108.6 pm/G at 100Hz, and it would be higher if the frequency is farther increased.

REFERENCES

[1] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication, Appl. Phys. Lett.,vol. 32, pp. 647–649, 1978.

[2] B. S. Kawasaki, K. O. Hill, D. C. Johnson, and Y. Fujii, Narrow-band Bragg reflectors in optical fibers, Opt. Lett.,vol. 3, pp. 66–68, 1978.Fiber Grating Sensors

[3] Kersey, A., Davis, M.A., Patrick, H.J., Leblanc, M., Koo, K.P., Askins, C.G., Putnam, M.A., Friebele, E.J., fiber grating sensors, 1997 , Page(s): 1442 - 1463

[4] J. M. Gong, J. M. K. MacAlpine, C. C. Chan, W. Jin, M. Zhang, and Y. B. Liao, A Novel Wavelength Detection Technique for Fiber Bragg Grating Sensors, Photonics Technology Letters, IEEE, 2002 , Page(s): 678 - 680

[5] Li Chuan, Zhang Yimo, Zhao Yonggui, Li Lijing, FBG: The principle, technology and sensing Applications, 2005.

[6] J. Chang, Q. Wang, X. Zhang, D. Huo, L. Ma, X. Liu, T. Liub, and C. Wang, A Fiber Bragg Grating Acceleration Sensor Interrogated by a DFB Laser Diode

[7] Dai Fing, Hang Guojun, An acceleration sensor based on Fiber Bragg Gratings, Laser Journal, 2005

[8] Stefani, Alessio, Andresen, Soren, Yuan, Wu, High Sensitivity Polymer Optical Fiber-Bragg-Grating-Based Accelerometer, IEEE PHOTONICS TECHNOLOGY LETTERS, 24(9), 763-765,2012

[9] Qi Jiang, Minghao Yu, Lingling Sun, Design and study of a vibrating string accelerometer based on fiber Bragg grating, The 6th International Symposium on Precision Mechanical Measurements,(ISPMM), Proc. of SPIE Vol. 8916, 89162N, 2013.8,8-12

[10]   Qi Jiang, Meng Yang, Simulation and experimental study of a three-axis fiber Bragg grating accelerometer based on the pull–push mechanism, Measurement Science and Technology,. vol.24,No.11, 115105 ,2013.1