A New Style of FBG Vibration Sensor

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***Abstract*- A new style of FBG vibration sensor with a special structure of metal three-legged stand and elastic cantilever is designed for many low-frequency tests of engineering structures and mechanical systems. It can work with a wide band, zoom in vibrating signal and increase sensitivity. And mathematical model of vibration sensor is established. Furthermore, natural frequency, sensitivity, distortion factor, horizontal anti-jamming capability of sensor were measured. Experimental results show that to detect vibrations below 75Hz is entirely feasible, with FBG vibration sensor designed. And its natural frequency is about 100 HZ, frequency range is 75 Hz, the resolution of amplitude is 0.3 nm/mm, sensitivity is 28.5 pm/m.s^{-2}.**

Keywords- Fiber Bragg Grating (FBG); Vibration Sensor; Demodulation

I. INTRODUCTION

It will produce less than 100 Hz vibration in many engineering structures and mechanical systems affected by environmental factors. For example road and railway bridge's natural frequency of vibration is around 2-10 Hz; engineering seismic pulse frequency is generally between 2 Hz and 50 Hz [1]. Accurate measurement and analysis of vibration phenomena for improving the quality and mechanical performance of the system is important. But traditional mechanical and electrical vibration sensors in the aspects of sensitivity, accuracy, dynamic range, and anti-electromagnetic interference et al. can no longer meet the application requirements. Fiber Bragg Grating Vibration Sensors technology can achieve an absolute measurement of physical quantities through the modulation of sensor signal's wavelength. The technology has high research value and broad application prospects in the sensor technology research field, for its advantages such as perfect capability of anti-electromagnetic interference, convenient conjugation with the WDM technology. Moreover, the equipment has light weight and small size [2-4].

The study on FBG vibration sensor began in the 90's of the last century. In China, Tsinghua University, Nankai University and other research institutions have done research on FBG vibration sensor from different angles. GONG Xiaofen [5] has reported that the natural frequency of FBG vibration sensor is 60 Hz and frequency bandwidth is 45 Hz. Although the sensitivity of FBG vibration sensor designed by SUN Ru-jiao [6] is high, its natural frequency is only 25 Hz and frequency bandwidth is less than 20 Hz. Besides, the sensitivity of it reported by Akira Mita [6] is low. Alberto Cavallo hasn't made specific sensor probe.

In this paper, a new style of FBG vibration sensor which has special structure of metal three-legged stand and elastic cantilever has been designed and its natural frequency is about 100 HZ, frequency range is 75 Hz, the resolution of amplitude is 0.3 nm/mm, sensitivity is 28.5 pm/m.s^{-2}. It is worth mentioning that the design of the tripod structure not only can zoom in vibration signals, but also improves the sensitivity of the sensor. In short, FBG vibration sensors designed can basically meet the demand in engineering and mechanical vibration measurements.

II. THE BASIC THEORY OF FBG VIBRATION SENSOR

It will cause Bragg reflection wavelength shift when the FBG is under longitudinal stress, and its formula is as following [9, 10]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - Pe)\varepsilon \tag{1}$$

Pe is the effective elastic-optic coefficient of FBG, ε is axial strain grating, λ_B is fiber Bragg grating wavelength, $\Delta\lambda_B$ is the peak change of Bragg wavelength. FBG sensor measures vibration parameters indirectly based the formula above. Special structure of the sensor can change amplitude, velocity, acceleration and other parameters into the axial strain, and then axial strain of cantilever causes changes in FBG Bragg wavelength. Finally, wavelength demodulation apparatus real-time detection changes of wavelength. In this way, the purpose of vibration measurement on the environment can be achieved.

The first part of equation is the attenuation and oscillations, and vibration attenuation is to zero by adjusting the damping coefficient in a short time. The second part of the solution is periodic vibration. The sum of two parts is the vibration response of the sensor, which best reflects the actual vibration environment. Therefore, we should select a siutable damping coefficient to ensure that damping oscillation decays to zero in a very short time. Finally, the sensor is in a stable vibration state (as illustrated in Fig. 2).

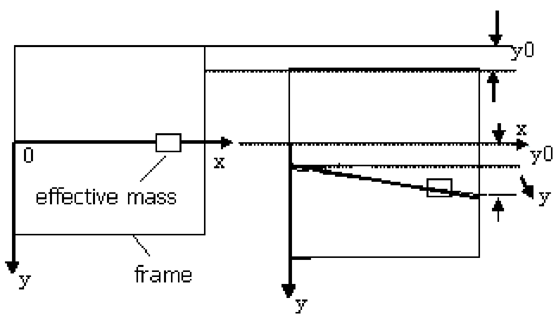

Fig. 1 Sensor equivalent model

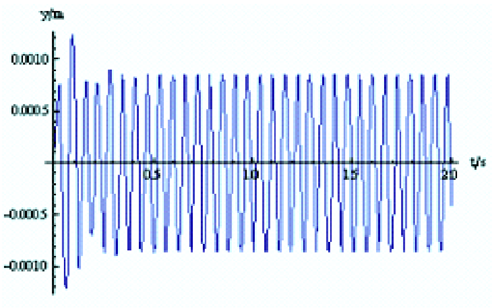

Fig. 2 Time history spectrum from vibration sensor

III. DESIGN OF FBG VIBRATION SENSOR

FBG vibration sensor is made of glucinfum bronze and its structure is uniform strength cantilever. FBG be pasted in the cantilever's axis near the fixed position. Special structure of metal three-legged stand and elastic cantilever is designed to increase sensitivity and reduce the quality and size of the sensor. The three-legged stand is cut and made from glucinfum bronze chip that is 2.2 mm thickness and equilateral triangle. And its expand plane is shown in Figure 3. Vibration energy can be quickly passed to axis position through the three legs of the cantilever. The structure is very sensitive to the weak vibration, as shown in Figure 4, because stainless steel screw and tripod center is connected in the end position of cantilever.

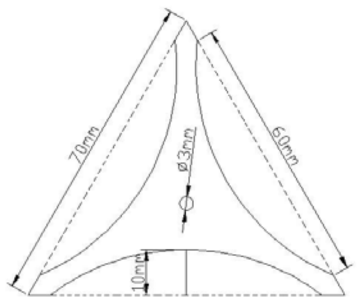

Fig. 3 The plan of tripod unfolding

Fig. 4 The structure diagram of tripod and cantilever

Mass keep vibration with vibration table in the cantilever's free end. It will cause Bragg reflection wavelength shift when the FBG Paste on the cantilever is under longitudinal stress because of the inertial force. Formula is as following [10]:

$$\frac{\Delta\lambda}{\lambda_B} = -(1 - Pe)\frac{3h}{2L^2\omega_n^{\ 2}}a \tag{2}$$

From this, wavelength change and acceleration change of vibration table is linear. We can achieve the goal of measuring acceleration by measuring the change in the wavelength of FBG; FBG vibration sensor's natural frequency [5] can be expressed as:

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{bh^3E}{4mL^3}} \tag{3}$$

The formula of FBG vibration sensor's sensitivity coefficients [5] is:

$$S = \frac{\Delta\lambda}{a} = -(1 - Pe)\frac{6Lm}{bh^2E}\cdot\lambda_B \tag{4}$$

Physical structure parameters are: elastic beam length, L = 49.55 mm, bottom width, b = 19.68 mm, thickness, h = 0.2 mm, elastic modulus, E = 128 GPa, mass, m = 3.41 g. We calculate the natural frequency and sensitivity coefficient, when not considering the impact of the Tripod structure.

$$\omega_n = 110.202\,Hz\ ;\ S = 12.22\,pm/m\cdot s^{-2}$$

IV. EXPERIMENTAL ANALYSES AND RESULTS

A. *Amplitude Resolution Analysis*

The amplitude resolution of FBG sensor is measured by the way of static measurement. We control the amplitude with micrometer caliper, while observing the changes in Bragg reflection wavelength in the spectrometer. The result is shown in Figure 5, in which it includes the measured data of increased amplitude and reduced amplitude. The data fitting result (increasing the amplitude) is:

$$\lambda = 1542.07 + 0.324887\,y_R\,,$$

Correlation coefficient: 0.99999, Linearity: 0.081%. The data fitting result (redusing the amplitude) is:

$$\lambda = 1542.06 + 0.325684\,y_R\,,$$

Correlation coefficient: 0.99998, Linearity: 0.094%. Two lines are coincident, indicating that the sensor has good reproducibility.

B. *Sensitivity Analysis*

The frequency of vibration table is fixed as 10 Hz, and then we observe Bragg reflection wavelength of FBG sensor changes with the acceleration, as shown in Figure 6. The equation of the data is: $\lambda = 1542.06 + 0.028477a$, Correlation coefficient: 0.99867, Linearity: 0.11%, Sensitivity: $28.5\,pm/m\cdot s^{-2}$. It is higher apparently than which shows that the sensitivity of tripod structure designed is largely increased.

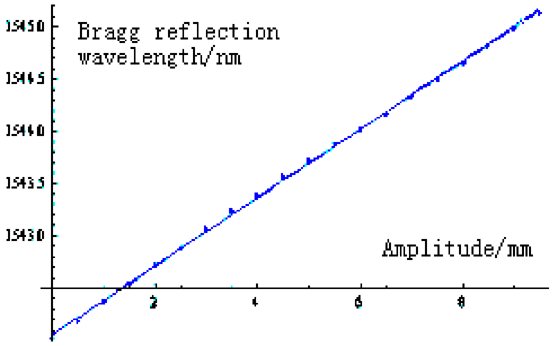

Fig. 5 FBG vibration sensor wavelength / amplitude curve

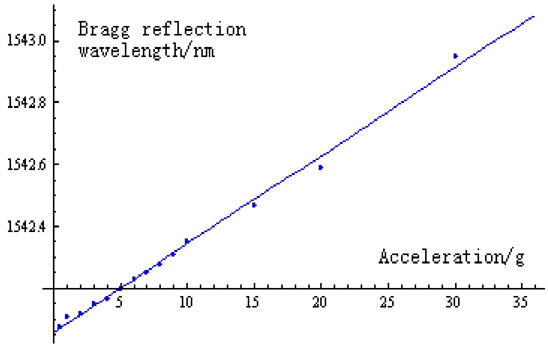

Fig. 6 FBG vibration sensor wavelength / acceleration curve

C. Analysis on Characteristics of Amplitude-Frequency

The acceleration of vibration table is set for the 1 g (g is acceleration due to gravity), and the range of measurement is from 0 Hz to 160 Hz for characteristics of amplitude-frequency. 100 Hz or so is the sensor's natural frequency from the experimental results of Figure 7, which are some errors, compared with the theoretical value 110.202 Hz. And the reason is that the beam's mass cannot be fully converted to the inertial mass. Although the design of the metal three-legged structure improves the sensitivity, and reduces the natural frequency of FBG vibration sensors. Some conclusions from Figure 7 can be obtained that 0-75 Hz is the flat areas of amplitude, 75-110 Hz is the resonance zone and above 100 Hz is the attenuation area. So 0-75 Hz is selected as a work area.

D. Analysis of Anti-Interference Ability [6]

The same acceleration (1 g) is imposed on the FBG vibration sensor in x and y direction. In this way, we can test its anti-jamming capability in x direction.The results is shown in Figure 8. The output of FBG sensor is about 1.05 V in y direction and the output of it is 0.035-0.051 V in x direction. Therefore, we can conclude that interference degree horizontal is 3.33% -4.86%, which has little effect on y direction.

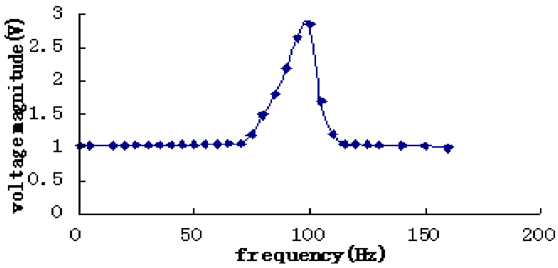

Fig. 7 FBG vibration sensor amplitude- frequency characteristic curve

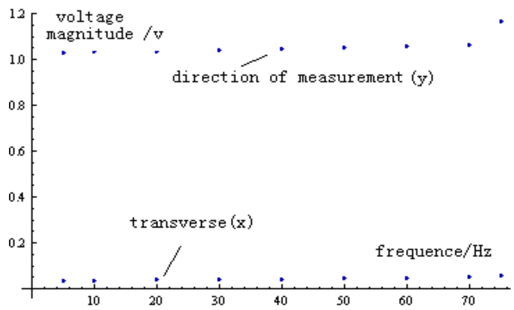

Fig. 8 characteristics to resist cross axis disturbance of FBG vibration sensor

E. Experiment on Measuring the Frequency of FBG Vibration Sensor

The method of sinusoidal excitation is used to test the measurement accuracy on frequency of FBG vibration sensor from 0-75 Hz. The results show that the accuracy is controlled within 0.9% and Figures 9-11 are the test results of 10 Hz. It is consistent with the theoretical analysis that there is a clear phase delay in the time domain response curve of vibration table and sensor. But some high-frequency interference caused by the noise from the photoelectric conversion and amplification circuit can be seen in graphics of the frequency domain analysis, which does not influence the accuracy of the results.

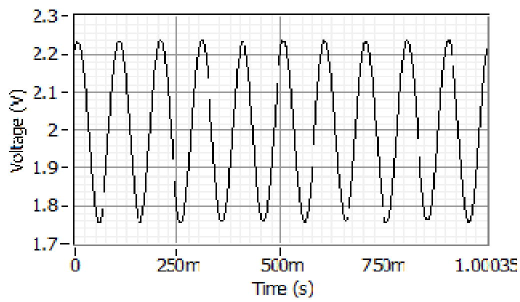

Fig. 9 Time history spectrum from vibration table

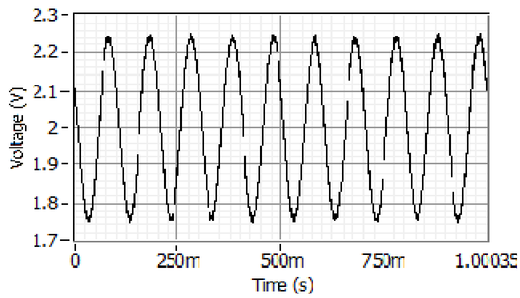

Fig. 10 Time history spectrum from FBG vibration sensor

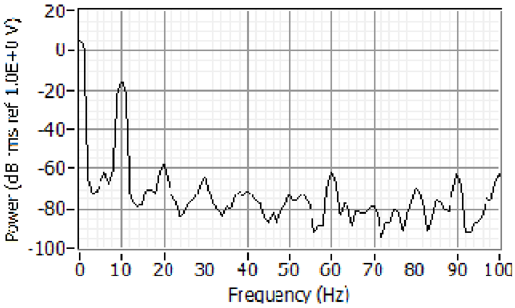

Fig. 11 Frequency spectrum from FBG vibration sensor

V. CONCLUSION

In this paper, a kind of FBG vibration sensor which has special structure of metal three-legged stand and elastic cantilever is designed. After the experiment, some important parameters, such as natural frequency (100 HZ), frequency range (75 Hz), the resolution of amplitude (0.3 nm/mm), sensitivity (28.5 pm/m.s^{-2}) and so on are derived, which can meet the needs of low-frequency tests of engineering structures and mechanical systems.

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