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Developing High-Frequency Fiber Bragg Grating Acceleration Sensors to Monitor Transmission Line Galloping

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ABSTRACT The traditional fiber Bragg grating (FBG) acceleration has a low operating frequency, which limits its application in transmission line galloping monitoring. We develop a slotting optimization technique to realize the accurate tracking of transmission line galloping in this work. Furthermore, this technique is applied to the development of a high-frequency FBG acceleration sensor. The width, position, and length of the slot are optimized to minimize the slot's effect on the FBG acceleration sensor. The vibration experiment in our work studies the frequency response and the sensing property of this FBG acceleration sensor. The experimental results indicate that our high-frequency FBG acceleration sensor has not only high sensitivity but also accurate monitoring results.

INDEX TERMS Acceleration sensor, high-frequency, fiber Bragg grating, transmission line galloping.

I. INTRODUCTION

With the global energy shortage and the need for environmental protection, Multi-energy optimization strategies have become a hot research topic in recent years [1]–[5]. Electrical energy, as a clean energy source, has received increasing attention from all countries. As a device for transmitting electrical energy, the state of the transmission line directly determines the reliable transmission of electrical energy.

Transmission line galloping frequently occurs in many circumstances. The transmission line under wind excitation will produce a self-excited vibration of low frequency and large amplitude, posing a threat to the reliable and safe operation of the transmission line [6]. To achieve the construction of a smart grid and reliable power grid, we need real-time monitoring and early warning for transmission line galloping.

So far, significant research efforts and progress have been achieved in the development of monitoring transmission lines galloping worldwide, such as manual monitoring, monitoring based on the principle of electrical measurement, and the method based on visual tracking [7]. Manual tracking, relying mainly on observation lines built-in dense ice areas where famous lines go through, set up observation station watched over by specially-assigned person recording meteorological information and waving situation. For existing lines, manual monitoring finds problems mainly through line attendant. By manual tracking, people can repair lines' problems timely, but significant errors can be involved. Because observation stations are located in the mountains, the work of line patrol is inconvenient and of high-cost. Monitoring based on the principle of electrical measurement breaks the limitations of traditional manual tracking. Still, its application is restricted because strong magnetic fields and power supplies influence electric measuring devices. Based on graphic monitoring, the method could describe the scene intuitively, vividly, and accurately, but in terms of transferring data and browsing images, the technology is not yet matured. In recent years, some methods have been applied to monitor the transmission line galloping [8]–[13]; they all have their characteristics and the scope of applications, though.

In this work, a slotting optimization technique is demonstrated, and then the method is applied to a high-frequency FBG acceleration sensor. Besides, the experiment has proved that the high-frequency FBG acceleration sensor can accurately monitor the existing transmission line galloping. So the application of this high-frequency FBG acceleration sensor

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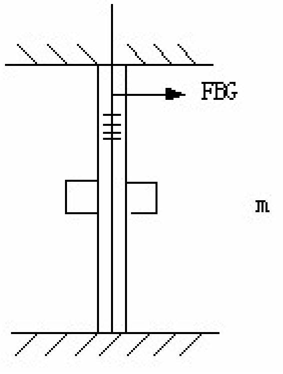

FIGURE 1. The structure diagram of high-frequency FBG acceleration sensor.

will reduce the immeasurable loss caused by transmission line galloping to the public life and social economy. It has essential values for engineering applications.

II. MODELING ELEMENTS AND PARAMETERS

A. THEORETICAL MODEL OF THE HIGH-FREQUENCY FBG ACCELERATION SENSOR

A high-frequency FBG acceleration sensor is made up of three parts, which are the inertial mass block m, FBG, and capillary steel tube. The structure diagram of the high-frequency FBG acceleration sensor is shown in Figure 1.

In this sensor, the mass m is subjected to the volume reaction forces. At the same time, the central wavelength of FBG is drifted because of longitudinal tension. Relationships of changes between the inertia force and FBG can be expressed as

$$ma = EA\frac{\Delta\lambda}{(1-P_e)\lambda} \tag{1}$$

$$A = \frac{\pi}{4}(d_1^2 - d_2^2) \tag{2}$$

Here a is the acceleration, E is the young's modulus of the fiber, A is the weighted cross-sectional area of the steel tube, d_1 is the external diameter of steel tube, and d_2 is the inner diameter of steel tube.

The sensitivity coefficient of the high-frequency FBG acceleration sensor is given by

$$\frac{\Delta\lambda}{a} = \frac{(1-P_e)\lambda m}{EA} \tag{3}$$

From this formula, with a fixed FBG, the bigger the inertial mass block m is, the bigger the sensitivity coefficient of the high-frequency FBG acceleration sensor is.

From formula (1), (2) and $\varepsilon = \Delta L/L$, Elastic coefficient k of the FBG sensing system is given by

$$k = \frac{EA}{L} \tag{4}$$

Here, L is the length of the steel tube.

The undamped natural frequency of the high-frequency FBG acceleration sensor is expressed as

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{EA}{mL}} \tag{5}$$

From formula (5), under the stable condition of FBG, the bigger the inertial mass m is, the smaller the natural frequency of the acceleration sensor system is.

B. PARAMETERS DESIGN OF HIGH-FREQUENCY FBG ACCELERATION SENSOR

The sensitivity coefficient and inherent rate are essential indexes for high-frequency FBG acceleration sensors. Because the natural frequency is reduced with the increase of the inertial mass, it needs the actual condition to select the inertial mass block when designing the sensor.

The resonance frequency is the natural frequency of the sensor. When the signal frequency is close to the natural rate, the output of the sensor will be in severe distortion due to the resonance. Therefore, the higher the resonance frequency is, the wider the working frequency band is. However, the frequency sensitivity is reduced with the increase of resonance frequency. According to the standard that the maximum working frequency is one fifth to one-third of the resonance frequency of the sensor, the natural rate of the sensor should be three to five times the maximum working frequency. The natural rate is given by formula (6):

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{EA}{mL}} = 3f_{top} \sim 5f_{top} \tag{6}$$

To increase the maximum working frequency of the sensor, the design parameters of the high-frequency FBG acceleration sensor are as follows:

The mass is a cylinder with a diameter of 20 mm, a height of 10 mm, and a weight of about 25 g. The length of the steel tube is 50 mm, the outer diameter is 1 mm, and the inner diameter is 0.8 mm. E is 200 GPa, and the center wavelength of the FBG is 1527.130 nm. Plug these parameters into formula (6), we can get that the natural frequency is 1254 Hz, the upper limit operating frequency of the sensor is between 251 Hz and 418 Hz, and the sensitivity coefficient of the sensor is about 20 pm/g.

III. FINITE ELEMENT ANALYSIS OF THE HIGH-FREQUENCY FBG ACCELERATION SENSOR MODEL

A. THE MODEL OF FINITE ELEMENT ANALYSIS

The long and thin pipe model is built by a shell element composed of a curved surface, which is formed of shell thickness midpoint. According to the actual boundary conditions, the degrees of freedom of all nodes, which are 15 mm far from the free end is restricted. The inertial mass block located in the middle of the long and thin pipe is simulated by using lumped mass units. The model uses the constitutive of linear elastic material. Its three material parameters include the material density of 7.8 g/cm3, elasticity modulus of 200 GPa, and the Poisson ratio of 0.28.

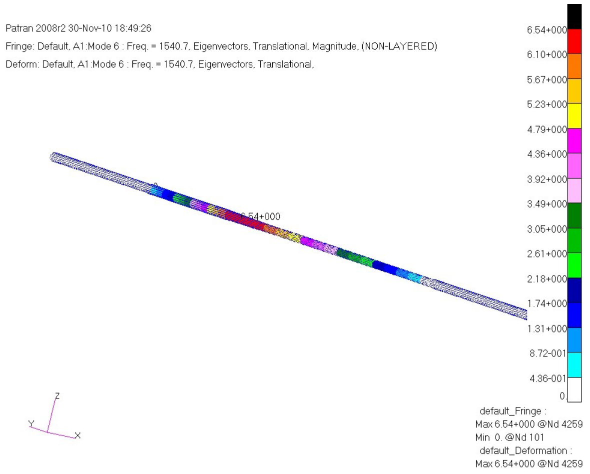

FIGURE 2. Vibration mode nephogram of the specimen.

B. THE MODAL ANALYSIS

By checking the correctness of the finite element model and obtaining the natural frequencies and inherent vibration mode of the specimen, the modal analysis is performed to choose excitation frequency reasonably and avoid resonance between the sample and vibration system.

Because colloids will be perfused into long and thin pipes in the experiment, specimens need to be slotted between the loading position and fixed end to cast efficiently. The slotting of samples needs to be optimized to reduce to a minimum in the vibration experiment. In the actual test, the range of vibration frequency is 0-300 Hz, and the direction of excitation is the same as the direction of the pipe. So we only need to analyze the first-stage natural rate of the specimen in the axial direction. The vibration mode program of the example in this natural frequency is shown in Figure 2. It can be seen from Fig. 2 that the rigidity of the sample is active along the axial direction, and the natural vibration frequency, reaching 1340.7 Hz, is much higher than the range of excitation frequency. Therefore, in the design of circular tube openings, we can utilize the MD Nastran topology optimization function, which the minimum flexibility of the specimen as an objective function and seeks the optimal distribution of the material. According to the above analysis, we can test the static strength of the optimized structure.

C. THE OPTIMIZED RESULT OF TOPOLOGICAL OPTIMIZATION AND STRENGTH ANALYSIS

After the optimization, the slotting way of the specimen is in Figure 3. The middle of the slot is the widest, and the width is reduced gradually along the axial direction. The length of the slot is about 8.07 mm, and the maximum width is 0.18 mm. The load position in the experiment is applied as a unifying force. The stress program of the specimen is in Figure 4. It can be known from Figure 4 that the maximum stress of the example fastens the edge of the slot and is about 4.07 MPa, while the mess of the middle of the sample is only 25 g. Even if the example receives 10 g acceleration excitation, the inertial force 0.25 N is less than the applied load in analyzation. According to the above analyses, the case after slotting meets the experimental strength requirements. Therefore the vibration test can be completed safely.

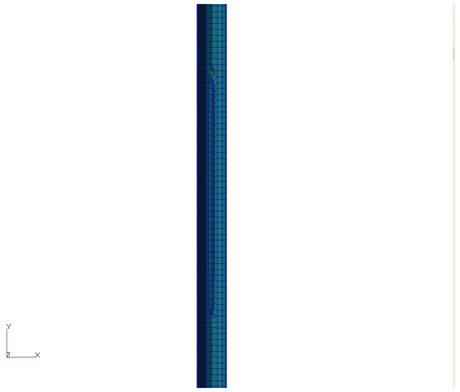

FIGURE 3. The slotting way of the specimen after optimizing.

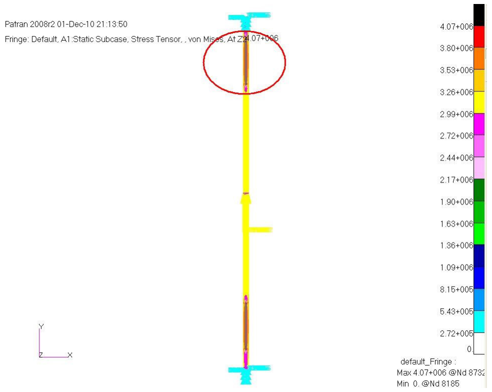

FIGURE 4. The stress nephogram of the specimen applied unit force.

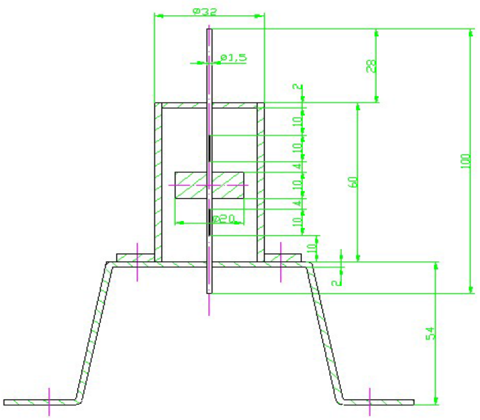

FIGURE 5. The workpieces of the high-frequency FBG acceleration sensor.

IV. VIBRATION EXPERIMENTS

A. EXPERIMENTAL DEVICES AND PROCESSES

According to the requirements, the molded workpieces are shown in Figure 5.

Our vibration system experiment is shown in Figure 6. The high-frequency FBG acceleration sensor is immobilized

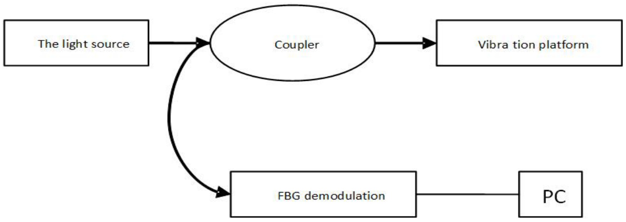

FIGURE 6. The vibration system experiment of the high-frequency FBG acceleration sensor.

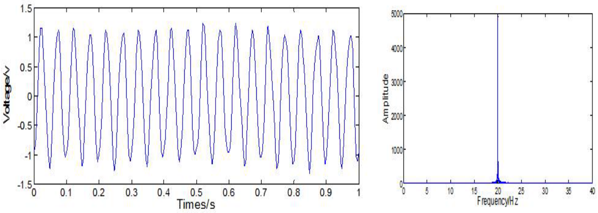

FIGURE 7. f = 20 Hz.

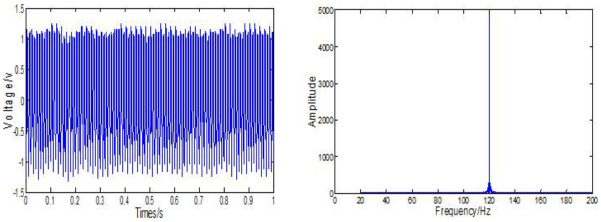

FIGURE 8. f = 120 Hz.

on the vibration platform. The FBG central wavelength is 1527.130 nm. The light source is ASE broadband light source, the wavelength is 800–2000 nm. The coupler is a 2 × 2 single-mode fiber coupler. The vibration platform is a vibration exciter, the frequency is 0-10000Hz. The demodulator is a portable demodulator based on photo detectors and the output voltage range is 0-5v. It can postulate that the sensor and vibration platform are of rigid connection. After the vibration platform begins to vibrate, the mass block of the sensor results in a deformation of the steel tube under the action of inertial force. At the same time, we can detect the FBG central wavelength shift by using a FBG demodulation system.

B. EXPERIMENTAL RESULTS AND ANALYSIS

The frequency and acceleration of the vibration system are monitored in our experiment. In our research, a = 2g, the range of vibration frequency is 0Hz to 240 Hz, and the space of vibration frequency is 20 Hz. Our experimental results are shown in Figures 7, 8, and 9. Due to a large amount of experimental data, only the vibration signal map and the spectrogram analysis of f = 20Hz, 120Hz, and 220Hz are selected. It can be seen from Figures 7, 8, and 9 that this acceleration sensor recovers the original signal better, and the result of spectral analysis is the same as the frequency of vibration signal.

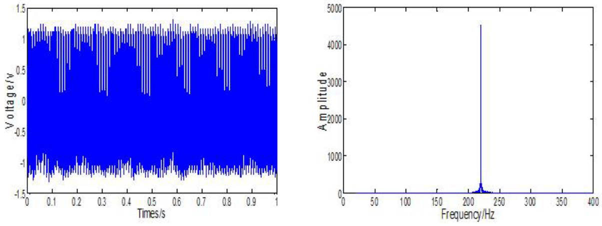

FIGURE 9. f = 220 Hz.

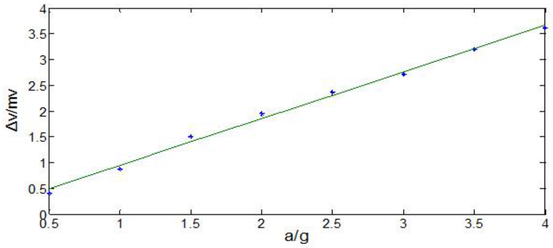

FIGURE 10. The relationship between acceleration and the voltage variation.

Our experiment verifies the acceleration characteristics of the acceleration sensor when it keeps the vibrational frequency as 20 Hz, the range of acceleration as from 0.5g to 4g with an increment of 0.5g. In the data analysis, the involved data is the maximum amplitude of the vibration signal of the acceleration sensor, namely the maximum wavelength change. Figure 10 shows that there is an excellent linear relationship between the variable quantity of wavelength of FBG and the acceleration. The linear fitting equation is $\Delta v = 0.9075\ g + 0.0398$, and the degree of the fitting is 0.9992. The sensitivity coefficient of the acceleration sensor is consistent with the theoretical analysis.

The high-frequency FBG accelerometer securely connects the FBG to the vibrating element through slotting on the workpiece. Slotting also makes FBG realize strain sensing better. Our experiment has verified that this high-frequency FBG acceleration sensor has useful vibration monitoring features, so it can be successfully used to monitor the transmission line galloping.

C. DISCUSSION

Although the FBG is sensitive to ambient variations especially temperature, but the experiments in this work are carried out in the laboratory and ambient temperature is stable. Hence, the effect of ambient temperature on the FBG can be ignored. If ambient temperature changes greatly, a temperature control is needed to ensure the temperature stability of the FBG.

At room temperature, we have repeated the preceding experiments and find that the sensitivity of the proposed system is almost invariable. So this system has good repeatability in sensitivity when ambient temperature is stable.

From Eq. (3), the sensitivity of this system is mainly relates to inertial mass block m and the weighted cross-sectional area of the steel tube A. As long as ambient temperature is stable, the sensitivity of this system is almost invariable. Thus, the stability of this system depends on the stability of ambient temperature. That is to say, this system will have good stability in sensitivity if ambient temperature is stable.

V. CONCLUSION

We have developed a slotting optimization technique and then applied this technique to a high-frequency FBG acceleration sensor. This optimization technique is to slot in the grid area of the FBG corresponding to the steel tube. At the same time, the width, position, and length of the slot are optimized by ANSYS analysis. Through studying the frequency response and the sensing property of this FBG acceleration sensor, the amplitude-frequency characteristic of this acceleration sensor is consistent with the underlying theory. By using the high-frequency FBG acceleration sensor to monitor dynamic vibration, the experimental results are accurate. So this high-frequency FBG acceleration sensor can be used to monitor the transmission line galloping. Thus we can get real-time monitoring of data and achieve early warning for transmission line galloping.

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