Fiber Bragg Grating Sensor Based Vibration Monitoring for Foreign Matter Invasion of Protective Barrier

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Abstract. A vibration monitoring system based on fiber Bragg grating is proposed to meet the need of protective barrier along the railway to monitor the foreign matter invasion. A high sensitivity fiber Bragg grating vibration sensor based on cantilever structure is developed. Three vibration sensors were deployed to a protective barrier with a length of 20 meters to conduct intrusion vibration monitoring test. Test results show that: 1) the fiber Bragg grating vibration sensor can well monitor the vibration signal; 2) the vibration intensity decreases obviously with the distance impact position increasing; 3) the response time of vibration measurement of different sensors is also in sequence when the distance impact location is different. Therefore, the magnitude of the external impact and the impact position in the protective barrier can be analyzed through the response amplitude distribution of each sensor and the response time sequence of the sensors.

1. Introduction
With the rapid development of China's high-speed railway, more and more attentions have been paided to the safety protection along the railway. Especially for the railway lines passing through mountainous areas, protective barriers have been installed seamlessly to isolate the railway lines[1]. However, it is inevitable that people or animals will cross, climb and even break into the railway, which poses a serious threat to traffic safety. Therefore, it is very important to carry out effective monitoring of the protective barrier. In the traditional video monitoring, staffs can not watch the monitoring screen all the time, and it is easy to miss some monitoring pictures[2]. Protective barrier will produce obvious vibration when invaded by person, animal or falling stone. This information can be used to monitor the invasion by detecting the disturbance information of the protective barrier[3]. Vibration sensors based on electromagnetic signals are susceptible to electromagnetic interference and lightning strikes. What’s more, the protective barrier where sensor is installed is near the power catenary of electrified railway, the system is susceptible to interference due to the large electromagnetic radiation. Sensors and transmission cables must be specially constructed and encapsulated, and lightning protection installed, which will increases the cost[4]. Fiber Bragg grating(FBG) sensors have received considerable attention in research publications and a wide range of applications have been implemented due to their advantages, such as immunity to electromagnetic noise, small size, light weight, ease of incorporation into a sensor network, and long signal
transmission distance[5, 6]. Therefore, Fiber Bragg grating sensor is very suitable for the field protective barrier monitoring.

This paper developed a fiber Bragg grating vibration sensor that can be installed and fixed on the protective barrier. Three sensors are arranged on the protection barrier to carry out tests of simulating the invasion vibration. Through analyzing the vibration measurement signal of the sensors, the method for invasion and the invasion position monitoring has been proposed.

2. The Basic Principle of Fiber Bragg Grating and the Design of Vibration Sensor

2.1. Principle of Fiber Bragg Grating

FBG is a periodic change of the refractive index in the core of a single mode optical fiber. When imported with a broadband light, the FBG reflects a specific narrowband range of the incident light. The central wavelength of the reflected light is just the Bragg wavelength $\lambda$, which can be described with the effective refraction index of the fiber core $n_{eff}$ and of the periodicity of the grating $\Lambda$ as [7]:

$$\lambda = 2n_{eff} \cdot \Lambda$$  \hspace{1cm} (1)

For an FBG with an initial central wavelength $\lambda$, the relationship between the wavelength shift $\Delta \lambda$ and the axial strain $\Delta \varepsilon$ and the ambient temperature change $\Delta T$ is:

$$\frac{\Delta \lambda}{\lambda} = (1 - P_e) \Delta \varepsilon + (\alpha_f + \xi) \Delta T$$ \hspace{1cm} (2)

Where $\alpha_f$ is the thermal expansion coefficient of the optical fiber, $\xi$ is the thermo-optic coefficient of the optical fiber, and $P_e$ is the effective elastic optical coefficient (about 0.22 at room temperature) of the optical fiber.

2.2. Design of Fiber Bragg Grating Vibration Sensor

As a classic elastic element, cantilever-based structures are commonly used in FBG vibration sensors design for the simple composition and stable performance. Constant strength cantilever can produce uniform strain distribution caused by bending and thus can avoid the phenomenon of chirped peak caused by the uneven strain distribution for FBG arranged on the beam surface. Thus, constant strength cantilever is chosen as the basic structure principle of vibration sensor. As shown in Figure 1, an FBG was attached on the beam surface, and a block mass was fixed on the free end of the beam. Under influence of external vibration acceleration, the beam vibrated with inertial force on the mass, generating alternating bending strain on the surface. This bending strain was detected and converted into wavelength shift by the FBG sensor. Thus, external vibration acceleration was retrieved using wavelength shift information detected by the demodulator. The inertial mass effect of the cantilever itself is ignored here.

![Figure 1. Structural schematic diagram of the designed FBG sensor](image_url)

Supposing the thickness of the beam with equal strength is $H$, the length is $L$, the width at the fixed end of the beam is $B$, and $x$ is the distance from the free end of the beam. Then the width of the beam at the fiber grating is $b_x = Bx/L$.

Bending moment of a beam of equal strength is:
Moment of inertia is:

\[ \text{I}_x = \frac{(b \times H^3)}{12} \]  

Then the strain for the FBG is equal to:

\[ \varepsilon_x = \frac{H}{2E} \times \frac{M_x}{I_x} = \frac{H}{2E} \times \frac{m_{ax}x}{(BxH^3/L)/12} = \frac{6mL}{EBH^2} \times a \]  

Where \( E \) is Young's modulus of the beam.

According to the relationship between the axial strain of FBG and its reflection wavelength \( \Delta \lambda_B = \lambda_B (1 - P_e) \varepsilon \), Relationship between external vibration acceleration and wavelength variation of FBG is:

\[ \Delta \lambda_B = \frac{6mL}{EBH^2} \times \lambda_B (1 - P_e) \times a \]  

Equation (6) is the basic measuring principle of the developed FBG vibration sensor.

A vibration test system was used to test the amplitude-frequency and linearity response of the vibration sensor. Impact method is typically used to investigate the frequency characteristics of the sensor. The time domain and frequency response of the designed sensor are shown in Figure 2(a). The experimental result shows that the resonant frequency of the designed sensor is around 70 Hz. As shown in Figure 2(b), acceleration performance test was repeated three times. Average data was fit to obtain sensitivity as 28.6 pm/g.

![Figure 2](image1.png)

**Figure 2.** Performance test of the FBG vibration sensor: (a) amplitude-frequency curve; (b) acceleration characteristics curve

![Figure 3](image2.png)

**Figure 3.** Field mounted: (a) Photo of the FBG sensor; (b) Specially designed fixture of the sensor; (c) photo of installed sensor on protective barrier
Figure 3(a) is the photo of the manufactured FBG vibration sensor, which was fixed on the protective barrier through specially designed fixture as shown in Figure 3(b). Figure 3(c) is the photo of the sensor installed on the protective barrier.

3. Impact Vibration Test on Protective Barrier

Three fiber Bragg grating vibration sensors are arranged on the surface of the protection barrier with a long distance to carry out the impact test under various circumstances and to study the response results of sensors. Figure 4 shows a protective barrier with a length of about 20 meters and the installation position of the three fiber Bragg grating vibration sensors. Three vibration sensors are arranged on both sides and in the middle of the protective barrier. From the schematic diagram, we assume that the leftmost protective barrier surface is 0 in length, and the three sensors are numbered 1, 2 and 3 from left to right.

The excitation of shock vibration is by knocking the protective barrier surface manually, and the intensity of each shock is basically the same. According to the structural characteristics of the protective barrier, there are many kinds of actual impact positions, and different impact positions may bring different vibrations. Two kinds of impact places, auxiliary foundation beam and net surface are selected and named as impact A and impact B. As shown in Figure 4, along the length of the grid, there are 5 position points at each tapping point, among which the five tapping points on the auxiliary foundation beam are respectively marked as A_1, A_2, A_3, A_4, and A_5, and their positions are 2, 6, 10, 14, and 18m, respectively. Strikeon points on net surface are respectively marked as B_1, B_2, B_3, B_4, and B_5, and their positions are 3, 7, 11, 15, and 19.5 m, respectively.

![Figure 4. The sensor arrangement of impact test](image)

![Figure 5. Response of sensor 1 and sensor 3 to impact test](image)
Striking A1-A5 and B1-B5 successively, the response characteristics of the same sensor to this gradually changing impact distance was studied, and obtain its amplitude by FFT transformation. Sensor1 and sensor 3 are arranged at both ends of the protective barrier, which are symmetrical relative to the center of the protective barrier. Firstly, the measurement results of hitting vibration of these two sensors are observed. Figure 5 shows the test results of two impact modes, it’s clearly that sensor 1’s the vibration intensity decreases obviously with the impact distance increases gradually. The test results of two different kinds of grille location are the same. As the impact position increases to the mounting position of sensor 3, the response vibration amplitude also increases significantly.

Secondly, the test results of sensor 2 installed in the middle of the protective barrier are observed as shown in Figure 6. The whole curve close to the gaussian distribution, and the response amplitude at the middle position is obviously larger, while the amplitude response caused by the impact at both ends far away from sensor 2 is small. The test results are consistent with the conclusions of sensor 1 and sensor 3.

Figure 6. Response of sensor 2 to impact test

Figure 7 is the comparison of the time-domain responses of sensor 1 and sensor 3 when striking B1. It can be clearly seen that there is a difference in response amplitude between the two sensors. The vibration time T1 of sensor 1, which is close to the tapping position, is earlier than the vibration time T3 of sensor 3 with a time interval of about 0.05 seconds. So, the magnitude of the impact and the impact position in the protective barrier can be analyzed by the response amplitude distribution of each sensor and the response time sequence of the sensors.

Figure 7. Time-domain responses of sensors 1 and 3 under the same vibration impact

4. Conclusions
This paper studies the vibration monitoring technology of railway protective barrier based on fiber Bragg grating. The developed vibration sensor is simple and reliable, and can measure the vibration
signal well. The vibration simulation experiment of the barrier intrusion is carried out, which proves that the magnitude of the external impact and the impact position in the barrier can be analyzed through the response amplitude distribution of each sensor and the response time sequence of the sensors. The research can provide an effective monitoring scheme for the safety monitoring and early warning of protective barrier.

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6. References
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