A loose self-checking method based on FBG for axle counting sensor

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Abstract. In order to improve the reliability and safety of the axle counting sensor, a loose self-checking method based on fiber Bragg grating (FBG) is proposed. FBG is used to detect the axial strain of the bolt which is a part of the axle counting sensor. It can effectively detect the installation condition of axle counting sensor. When the axle counting sensor is loose or fall off, the FBG wavelength will be lower than the set threshold value and an alarm signal will be sent. The experimental results show that the measured data of the loose self-checking device under different tightening torques are consistent with the simulation results. The artificial loosening test of the bolt is carried out, which proves that the method can be used to check the loose condition.

1. Introduction

Axle counter is a device to detect the number of axles passing through the sensing point of the railway, which is used to check the free or occupied condition of track section between two sensing points. As the basic equipment of rail transit signal, axle counter has been widely used in different engineering environments and line conditions. At present, the traditional axle counter is based on the principle of electromagnetic induction, which realizes axle counting by detecting the change of magnetic field when the train axle passes through the axle counter. However, the electromagnetic axle counter is prone to electromagnetic interference, which leads to axle counter error[1]. It often needs manual reset, which affects the driving efficiency.

As the development of optical fiber sensing technology, scholars focus on the research of grating axle counter. The fiber Bragg grating (FBG) axle counter is to use FBG strain sensor installed on the rail to measure the strain change when the train axle is pressed over the rail. It has the advantages of no electromagnetic interference and low cost, so that it can replace the traditional electromagnetic axle counter. The Hong Kong Polytechnic University presents a novel optical fiber sensor signaling system. The sensor operation, field setup, axle detection solution set, and test results of an installation in a trial system on a busy suburban railway line are given[2]. Wuhan University of technology has studied the train axle counter system based on Fiber Bragg grating, and the counting accuracy of the train axle has reached 100% in the experimental line for more than 1000 consecutive times [3]. Southwest Jiaotong University propose and demonstrate three FBG-based approaches for the strain measurement and axle counting in high-speed railway systems, and approaches are laboratory verified and evaluated using the train load platform[4].

However, the existing research results do not consider the impact of the long-term impact and vibration form the high-speed train, that will cause the FBG axle counting sensor loose. The axle
counting sensor situation of the FBG axle counter directly affects the results of the axle counter. If the axle counter sensor is loose or falls off from the rail, it will not be able to accurately measure the strain of the wheel axle pass the rail, and there is a risk of axle counter loss. Therefore, a self-checking method based on FBG is proposed for the first to detect the looseness of axle counting sensor. FBG is used to detect the pre-tightening force of mounting bolts, effectively detect the installation status of rail bottom mounting device, and send out alarm signal when detecting the looseness of mounting device.

2. Structure design of loose self-checking axle counting sensor

In order to install the FBG axle counter on the rail bottom reliably, an axle counting sensor with the function of loose self-checking is designed, as shown in Figure 1. The main components of the structure are rail bottom sensing shell (pink part), two clamp blocks (green part), two bolts (yellow part) and locknuts. By tightening the bolts, the sensing shell and clamp block at the rail bottom are clamped with the rail to make the sensing shell close to the rail bottom.

![Figure 1. The structure of axle counting sensor.](image)

When the bolt is tightened, there will be axial tension, which will cause the axial dimension of the bolt to increase and the transverse dimension to decrease. The relationship between bolt tightening torque and bolt axial preload is as follows:

\[ T = 0.2F \times d \]  

(1)

\( d \) is the diameter of the bolt. When preloading force \( F \) is applied axially to the bolt, the stress \( \sigma \) is generated on the cross section of straight bar with cross section area \( A \):

\[ \sigma = \frac{F}{A} \]  

(2)

Then the tensile deformation \( \varepsilon \) along the bolt axis is generated. According to Hooke's law, when the stress does not exceed the proportional limit of the material, the stress \( \sigma \) is proportional to the strain \( \varepsilon \):

\[ \varepsilon = \frac{\sigma}{E} \]  

(3)

\( E \) is the modulus of elasticity. In conclusion, the relationship between bolt strain \( \varepsilon \) and bolt tightening torque \( T \) is as follows:

\[ \varepsilon = \frac{4T}{0.2\pi d^3 E} \]  

(4)

It can be seen from the above formula that the axial strain of the bolt is directly proportional to the tightening torque of the bolt. Therefore, the FBG strain sensor embedded in the bolt can be used to measure the strain when the bolt is tightened. By monitoring the strain, the tightening condition of the bolts can be known, so as to know the installation condition of the axle counting sensor.

FBG sensing technology is used in the axle counting sensor with loose self-checking, and FBG strain sensor is used in the loose self-checking sensor. The reflection characteristic of FBG is shown in Figure 2. For the broadband light incident into the FBG, only the light shwith a certain wavelength can
be reflected, and the rest of the light is transmitted. The basic principle of FBG sensing is to transform the external changes (strain, temperature) into the shift of FBG central wavelength, and to measure the external parameters by detecting the shift of FBG central wavelength.

![FBG reflection characteristic diagram](image)

**Figure 2.** FBG reflection characteristic diagram.

The bolt is provided with a through hole along the axial direction. FBG strain sensing grating passes through the bolt through hole, and the nickel tube at both ends of the metallized optical fiber is welded on the bolt welding platform in the pre-stretching state, forming the loose self-checking bolt, as shown in Figure 3. In addition, because FBG can not only sense the change of strain, but also produce wavelength drift with the change of temperature, in practical use, there is another temperature compensation FBG without stress change.

![Installation drawing of FBG inside bolt](image)

**Figure 3.** Installation drawing of FBG inside bolt.

When installing, use a torque wrench to tighten the nut of the bolt so that the bolt is under tension. The center wavelength of FBG embedded in bolt increases. The center wavelength drift of FBG $\Delta \lambda$ is directly proportional to $\varepsilon$. From the formula, it can be seen that $\varepsilon$ is directly proportional to the tightening torque $T$, so the larger the tightening torque is, the greater the central wavelength drift of FBG is.

After installation, FBG optical sensing interrogator is used to monitor the center wavelength drift of FBG. When the wavelength change is less than the set threshold value, it indicates that the bolt is loose and the upper computer software sends an alarm signal.
3. Simulation analysis
Using ANSYS simulation software, the finite element model of axle counting sensor is established, as shown in Figure 4. By using this method, the law of bolt axial strain is simulated under different tightening torque.

![Finite element simulation model of axle counting sensor.](image)

![Simulation results of screw strain changing with tightening torque.](image)

**Figure 4.** Finite element simulation model of axle counting sensor.  
**Figure 5.** Simulation results of screw strain changing with tightening torque.

The simulation results of screw strain changing with tightening torque are shown in Figure 5. The simulation results show that the axial strain of bolt is $160.71 \mu \varepsilon$ under the action of $20\text{N} \cdot \text{m}$ torque, $321.42 \mu \varepsilon$ under the action of $40\text{N} \cdot \text{m}$ torque, and $803.55 \mu \varepsilon$ under the action of $100\text{N} \cdot \text{m}$ torque.

4. Experimental verification
The wavelength variation $\Delta \lambda$ of FBG embedded in bolt under different tightening torques is tested by experiment. According to the sensitivity coefficient of FBG is about $1.034\text{pm/}\mu \varepsilon$, the relationship between tightening torque and bolt strain can be obtained. The experimental test block diagram is shown in Figure 6. The loose self-checking bolt passes through the rail bottom sensing shell to fix the axle counting sensor and the rail. The optical fiber led out by the bolt is connected to the optical sensing interrogator. The optical sensing interrogator can demodulate the FBG wavelength and send it to the computer software through Ethernet. The computer software can display the FBG wavelength change, and then measure the bolt strain change.

![Test experiment diagram.](image)

**Figure 6.** Test experiment diagram.
4.1. Bolt tightening test

In the experiment, firstly, set the torque of torque wrench to 10N·m, fasten the bolt with torque wrench, and record the wavelength change of FBG at this time. Then set the torque of torque wrench to 20N·m, tighten the bolt, and record the wavelength change of grating. Increase the torque of 10N·m every time, and repeat the above process until the torque of torque wrench is increased to 100N·m. The experimental photo is shown in Figure 7.

**Figure 7.** Test photo of axle counting sensor with loose self-checking bolt.

In the experiment, the wavelength of FBG of two bolts change with tightening torque, as shown in Figure 8. The red dotted line is the test result of bolt 1, the green dotted line is the test result of bolt 2, and the blue dotted line is the simulation calculation result.

**Figure 8.** Test photo of optical sensing interrogator and computer.

**Figure 9.** Comparison of test and simulation results of bolt wavelength change under different tightening torque.

**Figure 10.** Wavelength change of FBG in bolt when train passing by.
Due to the randomness of FBG packaging technology in bolts, the sensitivity of FBG packaging in two bolts is different, so the test results of screw bolt 1 is slightly different from the test results of screw bolt 2. However, the test results are consistent with the growth trend of simulation results, which proves the effectiveness of the method.

4.2. Experiment on the influence of train over pressure on FBG in bolt

The process of 4 sets of wheel sets pressing over the axle counting sensor is recorded. The change of FBG wavelength is shown in the blue line in Figure 9, and the change of FBG wavelength in bolt is shown in the red line in Figure 10. The FBG wavelength in the bolt does not change more than ± 2pm when the wheel is pressed over the axle counting sensor, the FBG strain in the bolt is only related to the tightening state of the bolt, and is not affected by the train pressure.

4.3. Bolt loosening test

Manually loosen the mounting nut of the bolt with a wrench, and turn the wrench about 45°. It was observed that the wavelength change of FBG in loose self-checking bolt decreased more than 200 pm. Therefore, in actual use, the FBG wavelength value under the tightening state of the bolt and nut can be used as the reference $\lambda_0$, and the threshold value for detecting the looseness is $\lambda_0$ minus 100pm. When the FBG wavelength is lower than the set threshold value, the looseness alarm will be given.

5. Conclusion

In this paper, a method based on FBG for loose self-checking of axle counting sensor is proposed, and the loose self-checking device is made for experiment. The experimental results show that the measured data of the loose self-checking device under different tightening torques are consistent with the simulation results. The artificial loosening experiment of bolt verifies that when the bolt is loose, it can be checked by FBG wavelength change, which shows the effectiveness of the method. Subsequently, it can be widely used on the sensors installed on the rail bottom (such as FBG axle counter sensor, etc.), to realize the self-test alarm of sensor loosening or falling off.

References

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