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The Analysis of Angle Resolution of Stress Vector Sensor Based on Optical Fiber Sensing Cable for High Speed Railway Traffic

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Abstract: With the development of high speed railway traffic, the structure health monitoring for high-speed rail is necessary due to the safety issue. Optical fiber sensing technology is one of the options to solve it. Stress vector information is the important index to make more reasonable judgments about railway safety. However, information sensed by lots of commercial optical sensors is scalar. According to the stress filed distribution of rail, this paper proposes a new type of stress vector sensor based on optical fiber sensing cable (OFSC) with a symmetrical seven optical fibers structure and analyzes the relations between angle resolution and distance between adjacent of optical fibers through finite-element software (ANSYS) simulation. Through reasonable distance configuration, the angle resolution of the OFSC can be improved, and thus stress vector information, including the stress magnitude and the angle of stress, can be more accurately obtained. The simulation results are helpful to configure OFSC for angle resolution improvement in actual practice, and increase the safety factor in high speed railway structure health monitoring.
Key words: optical fiber sensing cable, rail, angle resolution, stress, finite element analysis
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0 Introduction

Optical fiber sensing technology has been booming since 1970s. With the advantages of optical fiber nature performance, such as high sensitivity and electromagnetic interference resistance, optical fiber sensing technology has been studied and applied in various fields[1]. The external stress or temperature and other environmental or complex climate have an impact on the refractive index of light for the core mode of optical fiber, so the optical signal carrying the sensed information can be received by the demodulator.

With the development of high speed railway traffic, high-speed rail, motor vehicles, subway and other transport have become the first choices for people travel. However, the structure health monitoring of rail does not satisfy the development of railway traffic demand. The demands of real-time, stability and accuracy of rail status information are getting higher[2]. Currently, the rail monitoring is mainly based on two technologies: the track circuit and the rail wheel gauge shaft. However, they are susceptible to electromagnetic interference, poor reliability and have other shortcomings[2]. Therefore, it is important to lead optical fiber sensing technology into railway traffic. In 2013, Tam's group has built the world's first city-wide Fiber Bragg Grating (FBG) sensing network to monitor all trains running in Hong Kong[3]. one single optical fiber with FBG is used to acquire information in order to monitor the structure health of rail. However, stress vector information cannot be obtained through one single optical fiber. Most importantly, it will be useful to understand the cause of the abnormal case happened in the rail with the help of vector stress. Therefore, the idea of optical fiber sensing cable (OFSC) is proposed to acquire stress vector information.

With the help of vector information, it can make a more accurate judgment and prediction of state of the rail, such as twisting and breaking. When the loading is applied on the rail, it will form a stress field distribution inside the rail. Through contacting with the rail, OFSC forms a stress field and strain stress field distribution inside it. Utilizing the difference of each optical fiber and the arrangement of optical fiber, the information of rail state can be acquired. At present, a great number of commercial optical cables are used for long haul communication systems and networks, instead of sensing. In addition, in the study of the stress characteristics of optical cables, most researches are

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based on optical communication cables[4], such as stress and temperature analysis on optical power ground wire (OPGW)[5]. For one thing, the arrangement of optical fibers in commercial optical cable is irregular, which means that there is no structural relation among those fibers loosely packed in one cable. For another, the gap between the primary coating and the secondary coating, usually filled with a water-repellent ointment, causes the two to slide relatively. When the external stress or factors influence the optical cable, the deformation of the cable does not directly act on the optical fiber, resulting in each optical fiber independent of each other, which induces the loss of vector information. For instance, OFSC is embodied in OPGW to monitor temperature and thermal strain variations by using Raman Effect[6]. Even though there are 24 optical fibers in the cable without a specific structure arrangement, the information derived from the direct or indirect results is still scalar.

Here the OFSC, we proposed, is composed of a plurality of optical fibers, which are arranged in the form of a specific symmetrical structure in the cable core, surrounded by a coating, protective jacket and other compositions. A structure with specific symmetry can be a quadrilateral, hexagonal, and so on. Optical fibers are arranged at the vertices of these structures. Because the external stress or other factors have different influences on each optical fiber, stress vector information can be acquired by these differences. Therefore, through using a specific symmetrical structure of optical fibers arrangement in OFSC, symmetrical characteristic can be utilized to analyze the difference of stress of optical fibers and then the vector information is derived. In addition, as for the engineering application of optical fiber in long haul optical communication systems, optical fiber sensor will be large-scale engineering applications too. Optical fiber sensors have been successfully embedded into soil for embedded cavity detection and sinkhole warming system in railway tunnels by using both Brillouin optical time-domain reflectometry (B-OTDR) and optical frequency-domain reflectometry (OFDR) sensing techniques[7]. Optical fiber sensor has been used for arctic pipeline leak detection by monitoring temperature changes[8]. Although the idea of OFSC has been proposed many years ago, it has not yet entered the stage of large-scale engineering application.

This paper describes the angle resolution analysis of stress vector sensor based on OFSC that is a symmetrical seven optical fibers structure. Firstly, finite-element analysis software (ANSYS17.2) is used to establish and simulate the structure of rail and then stress field distribution of rail is acquired. Secondly, the structure of OFSC based on a symmetrical seven optical fibers structure is established and simulated once again. Thirdly, the curves of the angle resolution, including the minimum outer stress in zero angle, the minimum angle in identical outer stress, and distance between adjacent optical fibers can be confirmed. Finally, we give a conclusion about the angle resolution to OFSC for railway traffic and discussion about future work.

1 The Modeling of Rail and Simulation

In order to know the stress field distribution inside the rail, the rail model is set up for simulation, as shown in Fig. 1. There is a 3D view of the rail when vertically applying the full loading. The type of rail is UIC-60, which is mainly made of Hadfield's manganese steel. In order to improve the effect of simulation, some relevant parameters which do not affect stress field significantly are simplified, as shown in Fig. 2. Figure 2 is the cross section of rail and it parameters. The length of rail is 550 mm, which is the distance of sleepers. The two ends of rail are fully restraint according to the reality. The loading is applied on the middle of the top of the rail through a small facet[9].

When 98 kN, the condition of full loading, is applied on the rail, there is a stress field distribution inside the rail. For the waist of rail, the maximum stress area is locating on the top and the two ends of rail, while the minimum stress area is locating around the bottom of rail. Therefore, the OFSC is embodied into or glued with the connection between the top and the waist of rail to sense the stress field by metal fusion, as

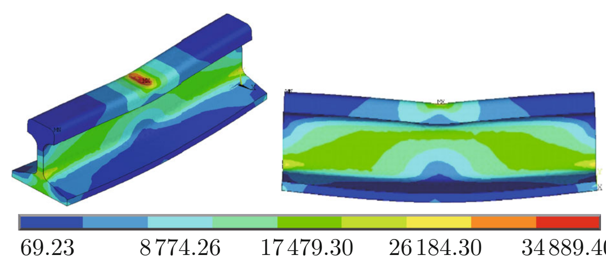

Fig. 1 Three-dimensional view of rail when vertically applying the full loading (N)

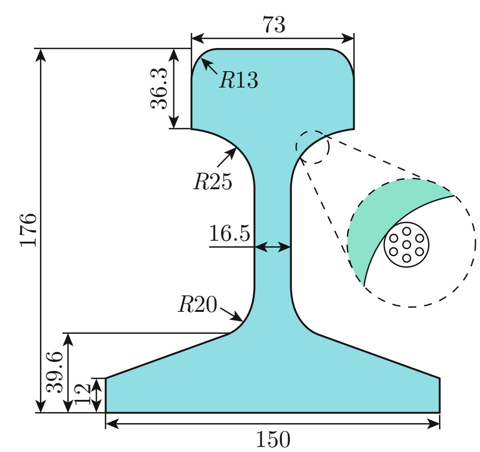

Fig. 2 The cross section of railway rail combining OFSC (mm)

shown in Fig. 2. When the magnitude and the angle of loading are changed, the stress field distribution of rail also changes and then affects stress field distribution of OFSC. Because of the existence of stress field distribution in OFSC, each optical fiber has different impacts on stress and strain.

Even though the OFSC is not installed straightly on the rail, it can be self-correcting to eliminate the influence by the initialization of sensing data analysis. What we care about is the relative value instead of absolute value. The relative value includes relative angle and magnitude. Firstly, the information of stress or strain field distribution is acquired by vertically loading on rail. Then this information is recorded as the reference. Everytime when the stress is transmitted to OFSC, this information is compared with the initial information so as to acquire a relative value.

The relation of stress and strain is

$$\sigma = E\varepsilon \tag{1}$$

where E is elastic modulus; σ is the stress; ε is the strain. Through analyzing the differences of stress or strain of each optical fiber and utilizing the symmetrical characteristic of OFSC, the information of external stress and rail state can be derived, so as to achieve the purpose of structure health monitoring of rail.

2 The Design and Modeling of Optical Fiber Sensing Cable and Simulation

2.1 The Design and Modeling

The OFSC structure based on symmetrical seven optical fibers structure is shown in Fig. 3. According to crystal physic, the close-packed hexagonal structure is one of the common and steady structures, which has the advantages of periodicity, symmetry and tightness. The angle of the adjacent vertices is 60° and so there are six equilateral triangles on the cross section. It has at least six symmetry axes. Therefore, the OFSC consists of symmetrical seven optical fibers which are arranged in a hexagonal manner and surrounded by the coating of silica gel, without a protective jacket. Silica gel, one of the filling materials, is used to transmit and buffer the outer stress since the full loading is too heavy. Besides silica gel is so steady that it is suitable for harsh environments. Optical fibers are placed at the vertices of hexagonal structures and at the middle of the cable core. The distance between adjacent optical fibers can be indicated as D and the diameter of optical fiber is 125 μm. For simplicity, the distance between outer optical fibers and outer coating is also 125 μm. Table 1 summarizes the elastic modulus and Poisson's ratio of the materials[10].

Utilizing finite-element software (ANSYS17.2), the simulation for angle resolution of OFSC is performed.

Table 1 The elastic modulus and Poisson's ratio of the materials

Material	Elastic modulus/MPa	Poisson's ratio
Optical fiber	7.452	0.17
Silica gel	2.55	0.499
Hadfield's manganese steel	2.08×10^5	0.3

Firstly, an ichnography of OFSC is set up and each optical fiber is numbered in a counterclockwise order, as shown in Fig. 3. Then the ichnography is extended into a three-dimensional map, as shown in Fig. 4. Here, the model length of OFSC is 2 mm. As shown in Fig. 3, the outer stress is applied on the middle of OFSC and above the No. 2 optical fiber. The angle θ stands for the angle of the direction of stress relative to the central axis at the same location. When the outer stress is vertically applied on the OFSC, the angle θ is equal to 0°. Smart meshing tool is used to mesh the model of OFSC and the contact of optical fibers with the coating is bound contact. Considering the efficiency and the accuracy, the solver of PCG is used for simulation. At last, the restraint is imposed at the vertices of OFSC at both ends.

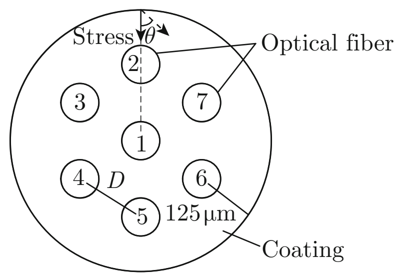

Fig. 3 The OFSC based on a symmetrical seven optical fibers structure

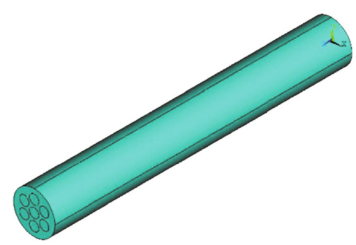

Fig. 4 The model of OFSC

2.2 Simulation

There are two indicators of angle resolution: the minimum outer stress $F_{\min}$ at $\theta = 0°$ and the minimum angle $\theta_{\min}$ in identical outer stress. As Section 2.1 said and shown in Fig. 3, the stress is applied on the middle of OFSC and the angle θ stands for the angle of the direction of stress relative to the central axis at the same location. According to Eq. (1), stress and strain have a close relation. Stress vector information can be acquired through strain field distribution inside OFSC. We choose $\varepsilon^{\circ} = 1 \times 10^{-6}\varepsilon$ as the strain resolution from the Canadian OZ company production[11].

For the minimum outer stress $F_{\min}$ at $\theta = 0°$, through applying different values of stress at $\theta = 0°$, the simulation results can be acquired to know that the $F_{\min}$ can be distinguished by OFSC. Firstly, when the distance D_0 between adjacent optical fibers is certain and the stress F_0 is applied at $\theta = 0°$, the strains of No. 3, No. 4, No. 6 and No. 7 optical fibers are acquired, representing as $\varepsilon_0^3, \varepsilon_0^4, \varepsilon_0^6, \varepsilon_0^7$. Secondly, the minimum strain $\varepsilon_{\min}$ of four optical fibers is

$$\varepsilon_{\min} = \left| \min_n \varepsilon_0^n \right| \tag{2}$$

where $n = 3, 4, 6, 7$. Through comparing the absolute value $\varepsilon_{\min}$ with ε°, if $\varepsilon_{\min} \neq \varepsilon^{\circ}$, then the value of stress F_0 increases or decreases accordingly. When $\varepsilon_{\min} = \varepsilon^{\circ}$, the value of stress $F_{\min 0} = F_0$ is the minimum outer stress distinguished by OFSC at this certain distance D_0. Thirdly, by changing the distance D and recording the minimum outer stress $F_{\min}$ at this distance, the curve about the distance $D_i\,(i = 0, 1, \cdots)$ and the minimum outer stress $F_{\min i}\,(i = 0, 1, \cdots)$ at $\theta = 0°$ is acquired.

For the minimum angle $\theta_{\min}$ in identical outer stress, through applying identical value of stress $F_{\mathrm{id}} = 100$ mN, at different angle θ, the simulation results can be obtained to know that the minimum angle $\theta_{\min}$ is distinguished by OFSC. The reason of taking $F_{\mathrm{id}} = 100$ mN as example is that most of the outer stress F applied on the OFSC is greater than 100 mN in actually. Firstly, when the distance D_0 between adjacent optical fibers is certain and the outer stress F_{id} is applied at $\theta_0 = 0°$, the strains of No. 3, No. 4, No. 6 and No. 7 optical fibers are acquired, representing as $\varepsilon_0^3, \varepsilon_0^4, \varepsilon_0^6, \varepsilon_0^7$. Secondly, the stress is applied at different angle θ_0^1 and then the information of $\varepsilon_0^{3,1}, \varepsilon_0^{4,1}, \varepsilon_0^{6,1}, \varepsilon_0^{7,1}$ is acquired. The minimum strain $\varepsilon_{\min 0}$ of four optical fibers at this angle θ_0^1 is

$$\varepsilon_{\min 0} = \min_n \varepsilon_0^n = \min_n \left| \varepsilon_0^{n,1} - \varepsilon_0^n \right| \tag{3}$$

where $n = 3, 4, 5, 7$. If $\varepsilon_{\min 0} \neq \varepsilon^{\circ}$, then the value of angle θ_0^1 increases or decreases accordingly. When $\varepsilon_{\min 0} = \varepsilon^{\circ}$, the value of angle θ_0^1 is the minimum angle $\theta_{\min 0}$ in F_{id} distinguished by OFSC at this certain distance D_0. Thirdly, by changing the distance D and recording the minimum angle $\theta_{\min}$ at this distance, the curve of the distance $D_i\,(i = 0, 1, \cdots)$ and the minimum angle $\theta_{\min i}\,(i = 0, 1, \cdots)$ in identical stress F_{id} are acquired.

The outer stress $F = 100$ mN is applied on OFSC at $\theta = 0°$. As shown in Fig. 5, there is 3D view of stress field distribution of No. 2 optical fiber. The seven optical fibers have the same characteristics and No. 2 optical fiber is taken as example. The location of maximum stress area is at the middle. The stress value decreases gradually from the middle to both two ends. The maximum stress value is about 140 μN and the minimum stress value is about 1 μN. Therefore, the 2 mN OFSC is enough for simulation.

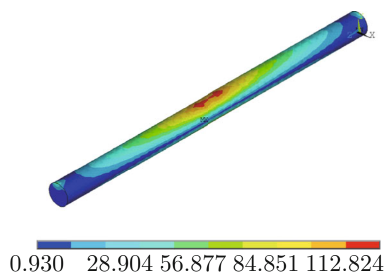

Fig. 5 The stress field distribution of No. 2 optical fiber (μN)

The reason why we just use No. 3, No. 4, No. 6 and No. 7 optical fibers is that symmetrical characteristic can be utilized to solve angle resolution problem. The outer stress which is applied on OFSC can be decomposed into the stress in the x direction and in the y direction. For one thing, the difference between group one (No. 3 and No. 7 optical fibers) and group two (No. 4 and No. 6 optical fibers) can give information about the stress in the x direction. For another, the diversity between group one (No. 3 and No. 4 optical fibers) and group two (No. 7 and No. 6 optical fibers) can give information about the stress in the y direction. Therefore, using that information can derive the stress vector information about angle. Besides, the No. 2 and No. 5 optical fibers may be used to confirm the magnitude of stress problem and the No. 1 optical fiber may be used for temperature monitoring, which is not the importance of this paper.

As shown in Fig. 6, this is the simulation result, including the minimum stress and the minimum degree. The tendency of two curves is almost identical and ascending with fluctuation as the distance increase. Polynomial is used to fit that curve and R^2 represents the goodness of fit. R^2 of the two curves is 0.9471 and 0.9615, respectively, which concludes that the polynomial curve is a good way to express the original curve. The reason why we do not simulate the strain at $D = 125$ μm is that the computer used for the simulation cannot calculate more finite elements. According to the polynomial fitting at $D = 140$ μm, the minimum stress $F_{\min}$ at $\theta = 0°$ is 1.26 mN and the minimum angle $\theta_{\min}$ in identical outer stress $F_{\mathrm{id}} = 100$ mN is 0.25°, which is satisfied for structure health monitoring of rail.

When the distance increases, the angle resolution will decrease with fluctuation. However, the smaller the distance, the harder it is to make the OFSC. Therefore, we need a reasonable distance configuration of OFSC.

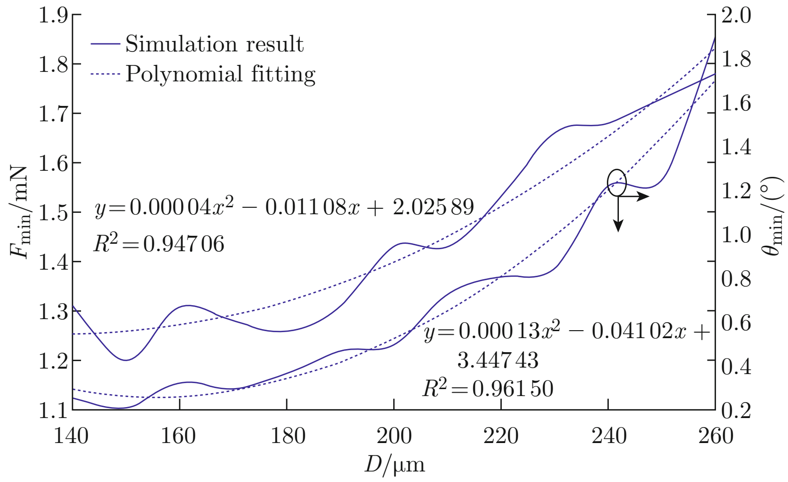

Fig. 6 The minimum stress and the minimum degree

3 Conclusion

A new type of stress vector sensor based on OFSC with a symmetrical seven optical fibers structure is proposed. Through the symmetrical arrangement of optical fibers and the differences of each optical fiber affected by strain field distribution, stress vector information can be acquired. The angle resolution has a great improvement due to reasonable configuration about the distance between adjacent optical fibers. When the distance is increases, the angle resolution will decrease with fluctuation. Simulation results for OFSC are helpful to guide the configuration of OFSC in high speed railway traffic.

Meanwhile, when changing some parameters, such as the diameter of optical fiber and adding the outer protective jacket, the curve of angle resolution will also change and the combination of different parameters to achieve the best angle resolution should be known. Then the method of judging stress vector information, including magnitude and angle of stress, should be discussed. Besides, the experiment on rail with OFSC should be verified whether the cable is suitable for the request of structure health monitoring of high speed railway traffic. What's more, in the face of different fields, the configuration of OFSC is also adjusted accordingly.

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