A Novel Optical Fiber Inclinometer for Railway Slope Deformation Monitoring

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Abstract: In this paper, a vertical-pendulum-based inclinometer using optical fiber extrinsic Fabry-Perot interferometer (EFPI) that can be applied to railway slope monitoring was proposed. A low-damping rotation structure was employed to reduce the mechanical rotation frictions in the pendulum system. Owing to the merits of white-light interferometric measurement and the novel rotation structure, high-resolution measurement of the tilt angle can be realized. Experiment results show that a sensitivity of 0.28 nm/'' and a resolution better than 0.011° have been achieved. Preliminary monitoring scheme for the slope deep deformation based on inclinometer was carried out.

Keywords: inclinometer; extrinsic fabry-perot interferometer; low damping rotation structure; slope deformation monitoring

1. Introduction

With the rapid development of railway construction, the problem of slope deformation along railway is becoming more and more severe. It is urgent to develop an effective method of railway slope deformation monitoring and early warning. Slope stability can be judged by monitoring the slope deep deformation especially the internal displacement, through which the potential sliding position and direction can be determined [1], and it is of great significance of the early warning and prevention of slope deformation disasters.

The traditional method of monitoring the deep slope deformation based on fiber-optic sensing usually attaches fiber gratings to the inclinometer tube to measure the bending strain and counter-infer the tube's sliding displacement, and then the deep slope deformation can be obtained [2]. However, this method has some defects: as the fiber gratings are directly attached to the tube, the grating chirp may be caused even the gratings will be pulled off when the tube is bend; moreover, sometimes the tube inclines with the slope sliding, but does not bend itself, which may result in the fact that the measured strain not totally reflect the slope deformation. In order to solve these problems, it is intended to measure the inclination angle directly by combining the inclinometer with the inclinometer tube, so that the slope deformation can be calculated more simply and accurately.

Inclinometers have been widely used in many fields, such as the civil infrastructure health monitoring, safety monitoring for petrochemical industry and electric power engineering, early warning of impending natural disasters such as landslides and earthquakes [3,4]. Conventional inclinometers are based on electric sensors [5]. Compared with electric inclinometers, fiber optic inclinometers have unique advantages such as immunity to electromagnetic fields, low transmission losses, the possibility of remote operation, etc. Several types of inclinometers based on fiber bragg grating (FBG) have been developed [6-9], but the resolution of these inclinometers is not sufficient for some applications that require high-precision tilt measurements. In recent years, researchers have paid attention to the applications of optical fiber interferometers in tilt measurement due to their robust structure, easy fabrication, and low cost [10].

In this paper, we propose an inclinometer can be used for slope deformation monitoring. It based on vertical-pendulum with a novel rotation structure, which use a blade edge and a V-shaped groove as the rotation part of the pendulum system to reduce the mechanical rotation friction. The extrinsic Fabry-Perot interferometer (EFPI) cavity is employed as the sensing head to achieve high-resolution measurement. Experiment results show that tilt angle sensitivity up to 0.28 nm/'' and resolution better than 0.011° can be achieved.

2. Sensor Design and Principle

2.1. Fabrication of the EFPI

The EFPI cavity is formed by the two optical fibers' endfaces that are strictly parallel and remain coaxially in the glass tube. The relationship between the variations of the cavity length ΔL_C and the tensile force F is satisfied with the Hooke's law $F = k \cdot \Delta L_C$, where k is the tension coefficient. Therefore, with proper structural design and packaging, an inclinometer based on EFPI cavity is able to be fabricated, which could be considered as a good candidate for inclination measurements.

2.2. Principles of the Inclinometer

The proposed pendulum-based inclinometer is shown in Figure 1. The sensor mainly consists of the following parts: the pendulum, the beam, the blade, the structural support and the base. The pendulum and the beam are fixed together, with a blade embedded in a slot between the two parts, and hanged on the V-shaped groove notched in the supporting structure, which is welded with the base. The blade and the V-shaped groove constitute the rotation part of the pendulum suspension mechanism. Because the contacting area of the blade edge and the V-shaped groove is very thin, rotational friction of the pendulum can be significantly reduced. The EFPI cavity is fixed at the middle position between the beam and the base. An optical fiber is straight and tightly glued at the symmetric position of sensor. This arrangement can reduce oscillations from environment-induced vibrations and increase the stability of the inclinometer.

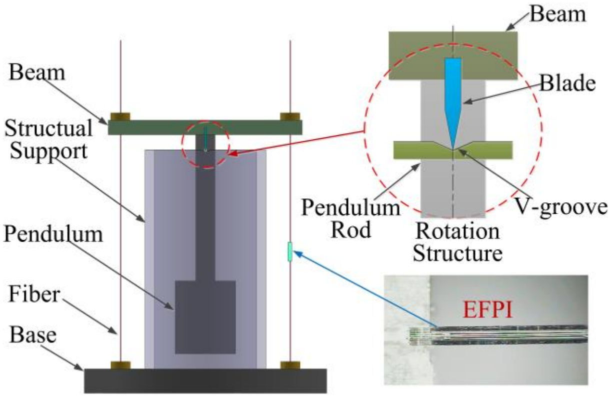

Figure 1. Structure of the proposed inclinometer and the blade edge type rotation structure.

Schematic diagram of the pendulum-based inclinometer is shown in Figure 2. The pendulum is kept in equilibrium by the fibers fixed to the sensor. When the sensor is inclined from the vertical position at an angle θ, the pendulum will move and the strain induced in the fibers vary due to the gravity effect of the mass block, resulting in the changes in the length of the EFPI cavity and the optical fiber when the fiber is tightened, leading to a tiny angle backward rotation of the pendulum.

The tilt angle θ applied on the inclinometer consists of two sections: the back-rotate angle θ_1 and the actual tilt angle θ_2. For small tilt angle, $\sin\theta \approx \theta$. According to the theory of mechanics of materials and force analysis in equilibrium condition, the sensitivity of the inclinometer can be calculated as

$$S = \frac{\Delta L_C}{\theta} = \frac{1}{\frac{2}{l} + \frac{2k \cdot l_f}{EAl} + \frac{k \cdot l}{2mgL}} \tag{1}$$

where Δl_C is the variations of the EFPI cavity length, l is the distance between two parallel optical fibers, l_f is the length of the fiber between the two fixing point, L is the length of the vertical pendulum, m is the mass of the pendulum mass block.The sensitivity can be improved by increasing the length L of the pendulum and the mass m.

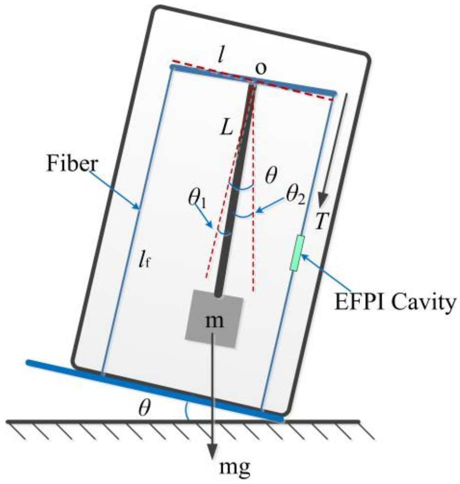

Figure 2. Schematic diagram of the proposed pendulum-based inclinometer.

3. Experiment and Discussion

The experimental setup is shown in Figure 3. The inclinometer is fixed onto a rotation table and covered by an encloser made of stainless steel to prevent external disturbance from making bad influence on the test. The demodulation system based on white light interference principle is established. The light waves travel through the lead-in optical fiber and undergo multi-reflections in the EFPI cavity of the inclinometer. The reflected light is spread over a Fizeau wedge, which can create a linear variation of thickness, resulting in reconstruction of the interference pattern. Cross-correlated interference pattern recorded by CCD has the maximum intensity at the position where the optical path difference equals the one created at EFPI of the inclinometer. The EFPI cavity length l_C corresponding to the tilt angle θ can be obtained by acquiring the position of the maximum peak in the CCD.

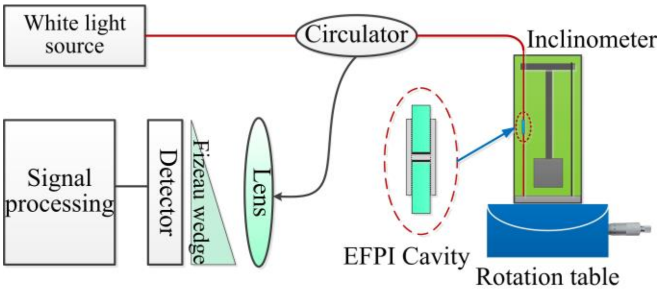

Figure 3. Experimental setup of the inclinometer.

The sensing head (EFPI) is connected to the demodulator, and the tilt angle is adjusted from 0° to 2° then backward to 0°, the whole process repeated for three times. The measured values of EFPI cavity length are plotted against the tilt angle, as shown in Figure 4. It can be seen that length of the EFPI cavity L_C has a good linear response to the inclination angle θ. The average measured tilt angle sensitivity is calculated as 0.28 nm/". The resolution of the inclinometer is up to 0.011° when the demodulator's resolution is 1 nm. The hysteresis less than 1.9% are demonstrated.

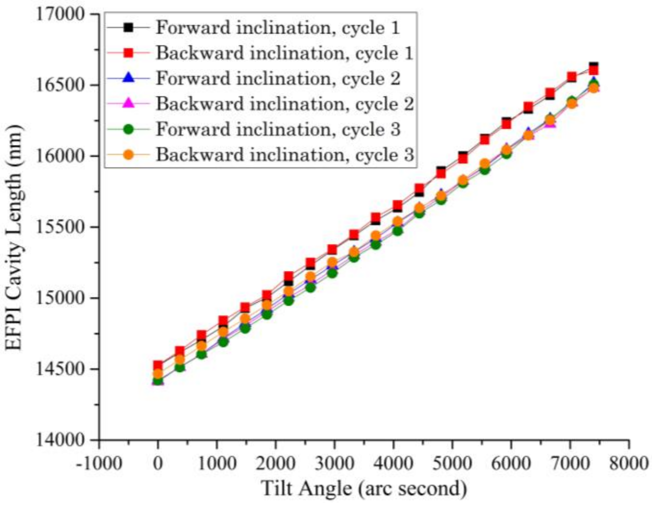

Figure 4. The relationship of EFPI cavity length and tilt angle.

The fabricated sensor is also put outside for 24 hours to test the temperature characteristics. The thermal expansion coefficient of the glass tube is consistent with the fiber by which inserted in, so the change in cavity length caused by temperature fluctuation can be offset. The experiment results show that there is no obvious correlation between EFPI cavity length and temperature, as shown in Figure 5. The maximum discrepancy of the cavity length is less than 9 nm during the temperature fluctuation in 24 hours, which implies that the proposed inclinometer is tolerable to the temperature variation during inclination monitoring outdoors.

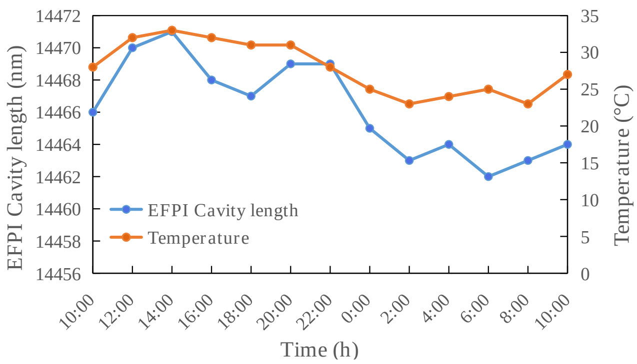

Figure 5. The EFPI cavity length and ambient temperature change over time in 24 hours.

4. Slope Deformation Monitoring Test Plan

The inclinometers are connected to form a sensor array fixed in the inclinometer tube in the same length L. Slope deep deformation will cause inclination of the tube and the inclinometers fixed in. The inclination angle of each length of the tube can be obtained, then the horizontal displacement S_i can be calculated by the formula $S_i = L \cdot \sin i$, thus the total horizontal displacement of the slope can be accumulated as follows

$$S_j = \sum_{i=1}^{j} d_i \quad (i=1,2,3\ldots) \tag{2}$$

The advantages of the method are as follows: Firstly, the inclinometer can be calibrated before installation so as to ensure the accuracy at each measurement point installing the sensors. Secondly, the inclinometers are able to obtain the inclination angle directly, which overcomes the obstacle that the measured strain can not reflect the tube' deformation accurately.

The coupling of the inclinometer and tube is realized by installing an external bracket on the sensor. In order to avoid damaging the sensor by shock and vibration during installation process, it is necessary to design a lock-pendulum device. Before monitoring, it is necessary to drill a vertical hole on slope subgrade to install the tube, and then pour cement mortar into the gap between the tube and the hole to ensure the two parts are in close contact and coordinate deformation. The top outlet of tube should be about 0.2~0.3 m above the surface of slope, and some protective measures need to be taken to prevent the invasion of foreign objects.

A remote slope deformation monitoring system can be established to achieve long-term automatic monitoring and early warning. The monitoring system consists of three parts: the sensor array, the field control room and the remote monitoring center, as shown in Figure 6. The demodulator, the data acquisition industrial computer, the local client and the GPRS terminal are placed in the field control room. The inclinometer array acquired the signal and sends it to the acquisition industrial computer for data processing and storage. Through the GPRS terminal, the monitoring data can be transmitted to the remote monitoring center by the GPRS network and the Internet for remote access, data analysis and disaster warning.

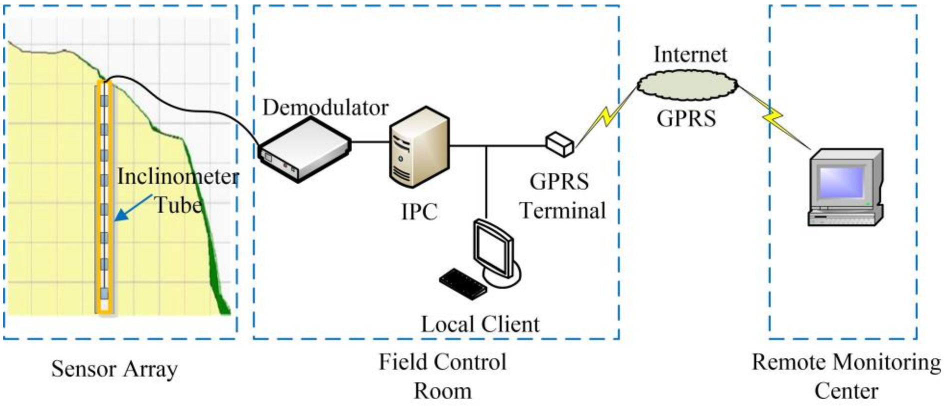

Figure 6. Structural Diagram of Remote Monitoring System.

5. Conclusions

In conclusion, a pendulum-based inclinometer using EFPI cavity as the sensing head and a simple rotation structure with low internal damping has been proposed. Owing to the merits of the white-light interferometric measurement and the specially-designed rotation structure, high-resolution inclination measurement is realized. In addition, the inherent friction in mechanical structures of the pendulum system can be reduced. The tilt angle sensitivity of 0.28 nm/" and resolution of 0.011° has been achieved. Importantly, the sensor stability is superior to traditional pendulum-type tilt sensors, which is reflected in a relatively better hysteresis less than 1.9%. The application scheme for the novel inclinometer for railway slope deformation monitoring is formulated, and the monitoring mechanism and installation process are preliminarily studied.

Acknowledgment

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References

[1] X. Deng, L. Zhu and J. Cheng. Study on Setting of Slope Displacement Monitoring Points by Numerical Calculation. *Civil Engineering and Technology*, **2013**, 2(2): 19-24.

[2] H.F. Pei, J.H. Yin, H.H. Zhu, et al. In-situ Monitoring of Displacements and Stability Evaluation of Slope Based on Fiber Bragg Grating Sensing Technology. *Chinese Journal of Rock Mechanics and Engineering*, **2010**, 29(8): 1570-1576.

[3] R. Aneesh, M. Maharana, P. Munendhar, et al. Simple temperature insensitive fiber Bragg grating based tilt sensor with enhanced tenability. *Applied Optics*, **2011**, 50(25): E172-E176.

[4] C. Gouveia, P.A.S. Jorge, J.M. Baptista, et al. Temperature-Independent Curvature Sensor Using FBG Cladding Modes Based on a Core Misaligned Splice. *IEEE Photonics Technology Letters*, **2011**, 23(12): 804-806.

[5] H. Jung, J.K. Chang, and S.H. Kong. An optimized MEMS-based electrolytic tilt sensor. *Sensors and Actuators A: Physical*, **2007**, 139(1-2): 23-30.

[6] B.O. Guan, H.Y. Tam, and S.Y. Liu. Temperature-independent fiber Bragg grating tilt sensor. *IEEE Photonics Technology Letters*, **2004**, 16(1): 224-226.

[7] H.J. Chen, L. Wang, and W.F. Liu, Temperature-insensitive fiber Bragg grating tilt sensor. *Applied Optics*, **2008**, 47(7): 556-560.

[8] H.Y. Au, S.K. Khijwania, H.Y. Fu, et al. Temperature-Insensitive Fiber Bragg Grating Based Tilt Sensor with Large Dynamic Range. *Journal of Lightwave Technology*, **2011**, 29(11): 1714-1720.

[9] Y. Wang, C.L. Zhao, L. Hu, X. Dong, et al. A tilt sensor with a compact dimension based on a long-period fiber grating. *Review of Scientific Instruments*, **2011**, 82(9): 093-106.

[10] Y. Zhuang, Y. Chen, C. Zhu, et al. Probing changes in tilt angle with 20 nanoradian resolution using an extrinsic Fabry-Perot interferometer - optical fiber inclinometer. *Optics Express*, **2018**, 26(3): 2546-2556.