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Regular Articles

Theoretical and experimental study on fiber-optic displacement sensor with bowknot bending modulation

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ABSTRACT

A novel and simple fiber-optic sensor for measuring a large displacement range in civil engineering has been developed. The sensor incorporates an extremely simple bowknot bending modulation that increases its sensitivity in bending, light source and detector. In this paper, to better understand the working principle and improve the performance of the sensor, the transduction of displacement to light loss is described analytically by using the geometry of sensor and principle of optical fiber loss. Results of the calibration tests show a logarithmic function relationship between light loss and displacement with two calibrated parameters. The sensor has a response over a wide displacement range of 44.7 mm with an initial accuracy of 2.65 mm, while for a small displacement range of 34 mm it shows a more excellent accuracy of 0.98 mm. The direct shear tests for the six models with the same dimensions were conducted to investigate the application of the sensor for warning the shear and sliding failure in civil engineering materials or geo-materials. Results address that the sliding displacement of sliding body can be relatively accurately captured by the theory logarithmic relation between sliding distance and optical loss in a definite structure, having a large dynamic range of 22.32 mm with an accuracy of 0.99 mm, which suggests that the sensor has a promising prospect in monitoring civil engineering, especially for landslides.

1. Introduction

Fiber-optic sensors have long been touted for their potential advantages over the conventional sensors, including immunity to electromagnetic interference, resistance to hostile environment, light weight, small size and potential for high precision noncontact measurement [1,2]. With the development of smart materials the offshoot technologies have also evolved. In particular, the use of optical fiber as sensors for measurement of mechanical quantities has seen a considerable growth, such as fiber-optic displacement sensors which have played an increasingly larger role in a broad range of industrial, military, and medical applications [3,4]. Two distinct ways are competent for this type of sensors: light source and reflective intensity modulation technique. The intensity modulation sensors have obtained many interests as they are simple and reliable in construction, low cost, et al.

There are two main categories for fiber-optic displacement sensors, i.e. extrinsic and intrinsic sensors. The reflexive-type [5,6], the transmission-type [1,7] and interferometric fiber-optic displacement sensors [8,9] are extrinsic sensors, which are widely applied in industrial systems due to those high accuracies and large ranges of measurement. The bend-loss type fiber-optic displacement sensor is also called the intrinsic sensor [10] that is a modulation sensor based on the principle that light transmission loss will increase suddenly under large curvatures. However, this type of sensor based on the principle of bending loss of optical fiber is widely used in structural engineering but rarely in geotechnical engineering, especially landslide monitoring. Sensors based on a fiber loop have been developed by Wolff and Messelier [11] and Ansari et al. [12]. For these sensors, the fiber loops are coupled to a concrete structure in such a way that cracking will induce change in the loop geometry and hence the amount of bending loss. The formation and opening of cracks can hence be monitored. The fiber-optic displacement sensor with the shape of a figure of eight was presented by Sienkiewicz et al. [13], show a sensitivity of 475 mV/mm over a 30 mm extension for civil engineering structure monitoring. A zigzag optical fiber micro-bending sensor was developed by Luo F. et al. [14], which can only be used to measure strain not large displacement because of its limitations of structural construction. Tang TG et al. [15] used the single optical fiber to monitor local slippage or deformation along the rock mass of the high slope with high initial accuracy (about 0.3 mm), but the very small sliding distance and dynamic range, 3.6 mm and

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Nomenclature

D,D_0	Dimension, initial dimension of symmetric bowknot
S	Retraction displacement of optical fiber
α	Bending loss of optical fiber
R	Curvature radius of bending optical fiber
ψ,ω	Constants to be confirmed, both are related to r, D, Δ
r	Core radius of optical fiber
D	Covering diameter of optical fiber
Δ	Relative refractivity
ξ	Deformation parameter of optical fiber and a function of time
η	Factor relating to optical fiber and formable material
l	Effective length of deformation of optical fiber
δ	Factor of refractive index of optical fiber
d	External diameter of optical fiber
σ	Refractivity of fiber core and covering
ρ	Polar radius
θ	Polar angle
a	Constant related to the length of leaf
L	Perimeter of symmetric bowknot
$E(\frac{\sqrt{3}}{2})$	Value of the second kind of ellipse integral that is constant and can be known via the table of elliptic integral
C_1,C_2	Constants to be confirmed which are related to r, d, Δ and initial loss of optical fiber

0–3.3 mm, respectively, prohibit large deformation monitoring usage. In our previous study [16], the application of the combined optical fiber transducer (COFT) based on bending loss technology of optical fiber in deformation monitoring of a slope was presented, but we have not better understanding of the COFT and simple data fitting was considered as the result of calibration without any physical meanings, which may result in the accuracy and reliability of monitoring results being uncertain. To identify suitable applications of the COFT, a good understanding of the principles and advantages of this sensor is required.

In this paper, we present a novel and simple type of fiber-optic sensor with a bowknot bending modulation which can increase the fiber's sensitivity to detect the deformation of structures, having a large displacement range and high accuracy of measurement. The sensor can be mounted in the structures to measure deformation. A theoretical model formulated based on the geometry of sensor and principle of optical fiber loss is proposed to calculate the light loss and the output signal of sensor. We fit the experimental data to the theoretical model to further confirm the working principle, and obtain a fully consistent agreement between theory and experiment. Furthermore, the direct shear tests on six physical models constructed with the fiber-optic displacement sensors and base materials with different cement mortar ratios were conducted to simulate the shear failure in the process of landslide, finding that the fiber-optic displacement sensor and base materials can be used for monitoring sliding damage with a large sensing distance and high accuracy. Therefore, the sensor presented in this paper will be a potential prospect and application in civil engineering, especially landslide monitoring, et al.

2. Structure of the sensor

The sensitivity of untreated optical fibers is insufficient to detect the deformation of structures in bending. To increase the fiber's sensitivity to curvature, a sensitive zone is designed as a bowknot (see in Fig. 1a) which will causes a large number of losses (called "sensitive zone") and similar to the shape of a figure of eight (see in Fig. 1b) of the fiber-optic displacement sensor introduced by Sienkiewicz et al. [13], where the dimension of D (namely, the horizontal distance between points A and B, the two points have maximum curvature) will be referred to as sensor size and S as gaze length. The geometry allows the natural stiffness of

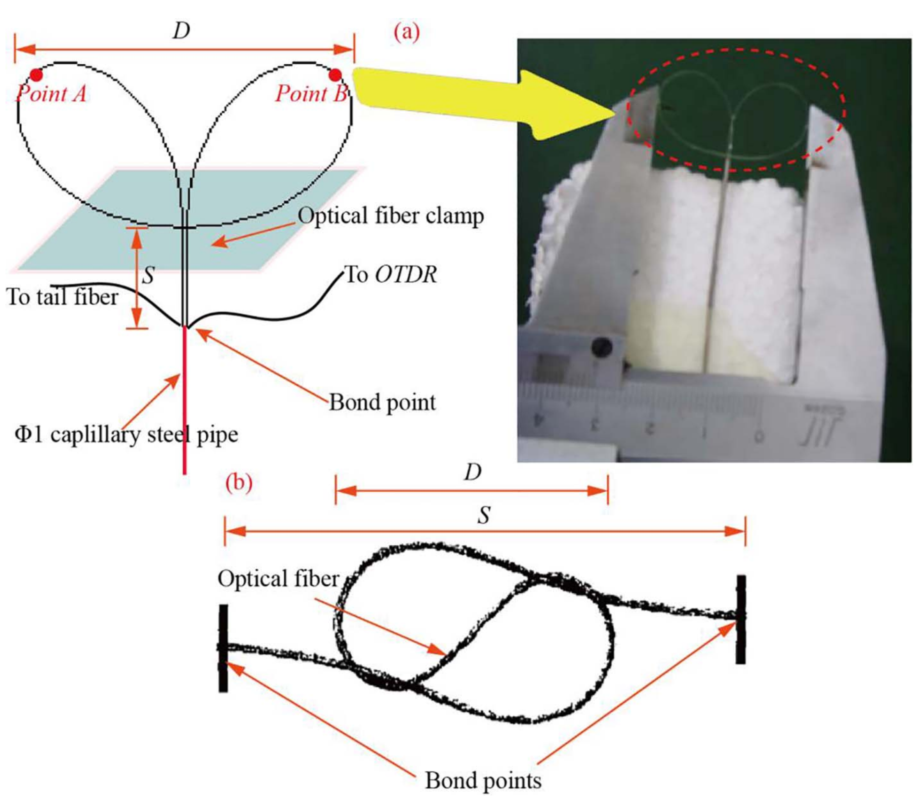

Fig. 1. Sketch of the fiber-optic displacement sensor (a) Bowknot bending modulation of the proposed sensor (b) Fiber-optic displacement sensor with shape of a figure of eight [13]