Sensors and Actuators A 272 (2018) 53–61

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# The sensing principle of a new type of crack sensor based on linear macro-bending loss of an optical fiber and its experimental investigation

Lin Cheng*, Yaming Li, Yuming Ma, Minghao Li, Fei Tong

*State Key Laboratory of Eco-hydraulic in North west Arid Region of China, Xi'an University of Technology, Xi'an, 710048, China*

ARTICLE INFO

*Article history:*
Received 20 November 2017
Received in revised form 17 January 2018
Accepted 28 January 2018
Available online 31 January 2018

*Keywords:*
Distributed optical fiber sensors
Macro-bending loss
Crack opening displacement (COD)
Experimental investigation

ABSTRACT

For traditional distributed optical fiber sensors, the sensing principle is based on a complex relationship between the crack opening displacement (COD) and the macro-bending loss of the fiber, which introduces many difficulties in its application in practical engineering projects. To solve this problem, a simple linear relationship between the macro-bending loss of the fiber and the COD is established in this work by controlling the fiber winding shaft to ensure the bending radius remains constant. Based on this linear relationship, a crack sensing principle of optical fiber is proposed. To verify the feasibility of this crack sensing principle, a validation experiment was performed using three groups of fiber winding shafts with different diameters and three groups of working light sources with different wavelengths. The experimental results show that the macro-bending loss is linearly related to the COD. Based on the proposed crack sensing principle, and a new type of optical fiber crack sensor to monitor the COD of pre-existing cracks and contraction joints of structures is designed, and the performance is verified by an experiment.



## 1. Introduction

The application of optical fibers in the field of communication and sensing is developing rapidly because of its advantages, such as wide frequency band, strong anti-jamming capability, light quality, small volume, good corrosion resistance, good electrical insulation and safety and reliability [1–8]. In practical applications, the optical fiber is prone to bend, resulting in macro-bending loss, which is detrimental for long-distance optical signal transmission. However, the macro-bending loss of optical fibers in the field of fiber sensing is favourable. Consequently, the external physical quantities can be modulated via changes in macro-bending loss to realize sensing in fiber macro-bending loss [9]. A distributed optical fiber sensor is a continuous fiber that has sensing and light guiding roles; the fiber receives the distributed information of the measurant along with the time and position.

Some crack sensors based on the macro-bending loss of optical fibers have been proposed. Leung et al. [10–12] devised two novel distributed optical crack sensors for concrete structures. One of the sensors is a rectangular polymer sheet with Z-shaped fibers, and the sheet is pasted on the bottom of the structure to be tested. When the structure suffers cracks, the polymer sheet deforms, causing the fibers to bend. Using the Optical Time Domain Reflectometer (OTDR), the position and scale of the cracks can be detected via the light attenuation and degree of attenuation. The other sensor has a fiber ring on each side of the polymeric plate from the first sensor. This sensor detected two cracks in the bottom of a beam during a single point loading test; however, the sensor has a small range. Taking this into account, Bao et al. [13,14] created a large-range fiber crack sensor. The sensor contains a bare fiber coil, and the ends of the bare fiber coil are fixed to the sides of the concrete structure where cracks may occur. The cracks cause a decrease in the bare fiber coil to produce a macro-bending loss. The monitoring range of the sensor was expanded to 26 mm. Luo et al. [15] also devised a novel sensor structure. The fiber is spirally wound onto a rubber hose. The deformation of the structure causes a change in the curvature of the fiber coil, resulting in a macro-bending loss. The monitoring range of the sensor was expanded to 17 mm; however, it has a poor productive ability. To overcome such a deficiency, Zhu et al. [16] inserted a bare fiber into a steel capillary tubing and created a butterfly ring at the end of tubing. With this structure, the sensor is buried in concrete. The bending degree of the tubing is changed as the cracks change. As a result, the productive ability improved. However, the sensor is inadequate

* Corresponding author.
*E-mail address:* wanmu2381@163.com (L. Cheng).

https://doi.org/10.1016/j.sna.2018.01.056
0924-4247/

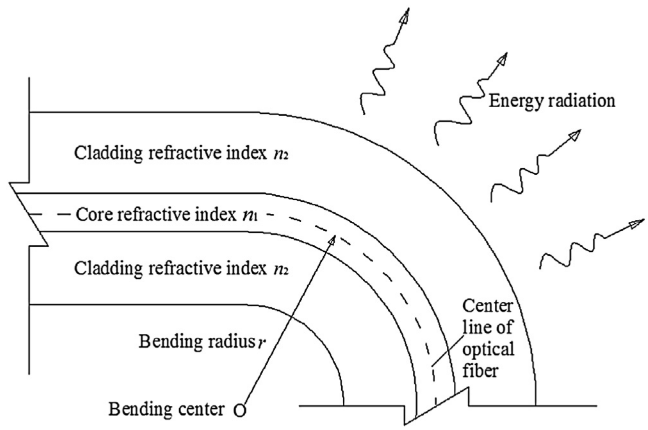


**Fig. 1.** The radiation of the bending optical fiber waveguide.

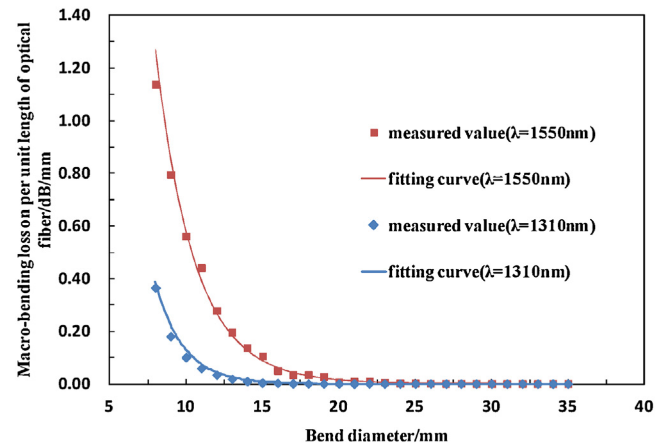


**Fig. 2.** The macro-bending loss per unit length of optical fiber for the G652D optical fiber and the light source with a wavelength of 1310 nm or 1550 nm.

for monitoring tiny cracks. Thus, to improve the ability to monitor tiny cracks, Zhao et al. [17] proposed a six-prism structure for a distributed fiber crack sensor. When cracks occur to a certain degree, the fibers wound on the hexagonal prism bend in each corner, greatly increasing the sensitivity of the sensor; in addition, the sensor can effectively monitor tiny cracks between 0–0.8 mm. In the above studies, the macro-bending loss of the fiber has a complex, nonlinear relationship with the bending radius of the fiber; thus, the relationship between the strain or crack opening displacement (COD) measured by the fiber distortion gauge and the macro-bending loss of the fiber is also a complex, inhibiting the application of fiber macro-bending loss sensors in practical engineering.

In this work, a new crack sensing principle based on optical fiber macro-bending loss is proposed, and a fiber optic crack sensor to monitor the COD of pre-existing cracks is designed. The main content of this paper consists of 3 parts. In Section 2, the new crack sensing principle based on optical fiber macro-bending loss is introduced, and the structure of the new type of optical fiber crack sensor is designed. In Section 3, an experiment is performed to validate the crack sensing principle. In the Section 4, the performance of the new type of distributed optical fiber crack sensor is verified through two different experiments.

## 2. Crack sensing principle based on linear fiber macro-bending loss

As shown in Fig. 1, when an optical fiber is bent, energy will emit along the bending radius of the fiber, and the original guide modes in the optical waveguide will become a radiation mode, causing bending loss. The loss that occurs when the bending radius of the curvature is much greater than the fiber diametric bending is known as macro-bending loss. The main reason for the macro-bending loss is the spatial filtering effect, which is a physical effect caused by the destruction of the total reflection conditions of the wave propagation, resulting in energy radiation outside of the fiber. The greater the degree of fiber bending, the more obvious the spatial filtering effect, the fewer modes in the fiber transmission, and the greater the loss of fiber transmission.

For the step-index single-mode fiber, the macro-bending loss per unit length, $a_c$, can be expressed as [10,18]:

$$a_c = A_c r^{-\frac{1}{2}} \exp(-Ur) \quad (1)$$

where $r$ is the macro-bending radius of the fiber, and $A_c$ and $U$ are the amounts associated with the fiber types and working states of the light source, respectively, given by:

$$A_c \approx \eta \Delta^{\frac{1}{4}} \lambda^{-\frac{1}{2}} \left(\frac{\lambda}{\lambda_c}\right)^{\frac{3}{2}} \quad (2)$$

$$U \approx \delta \Delta^{\frac{3}{2}} / \lambda (2.748 - 0.996 \lambda_c / \lambda)^3 \quad (3)$$

where $\lambda$ is the working length, $\lambda_c$ is the cut-off wavelength, $\Delta = (n_1 - n_2)/n_2$ is the difference between the relative refractive indices of the optical fiber core and the cladding, $n_1$ is the core refractive index, $n_2$ is the cladding index, and $\eta$ and $\delta$ are constants related to the fiber types and working states of the light source, respectively.

It can be seen from the Eqs. (1)–(3) that, in theory, when the wavelength of the light source, $\lambda$, the cut-off wavelength, $\lambda_c$, of the fiber, the bending radius, $r$, of the optical fiber and the relative refractive index difference, $\Delta$, between the fiber and the cladding are fixed, the macro-bending loss on per unit length of optical fiber, $a_c$, is a constant.

For the G652D optical fiber (which will be adopted in our following experiments) with a light source with a wavelength of 1310 nm or 1550 nm, the macro-bending loss per unit length of optical fiber is shown in Fig. 2 from our experiments. Two empirical formulas are shown as follows:

$$a_{c1310} = 38.9040 r^{-0.5} e^{-0.979886r} \quad (4)$$

$$a_{c1550} = 38.1519 r^{-0.5} e^{-0.677047r} \quad (5)$$

The traditional distributed fiber crack sensor adopts the principle that the change in the bending diameter causes an optical loss. As illustrated in Fig. 2 and Eqs. (4) and (5), the bending diameter of the fiber is exponentially related to the macro-bending loss in per unit length. This complex relationship between the structural COD and the macro-bending loss measured by the sensor makes it inconvenient to use the traditional sensors in practical engineering. Moreover, the measurement accuracy is usually unsatisfactory.

In this work, a new type of crack sensors based on optical fiber macro-bending loss is designed. As shown in Fig. 3, the main components of the new type of optical fiber crack sensor include the following: base, optical fiber winding shafts, gears, rack, bearing, pull rod and fixing nuts. The optical fiber winding shafts are covered by the upper bearing, gear and lower bearing in turn, and the two gears are engaged with each other. The rack E, which is fixed with a slider on the top, is engaged with gear C. The slider can move around via the hole in the base. One side of rack E is fixed with a pull rod that can extend out of the sensor through the hole in the