A fiber optic microbend sensor for distributed sensing application in the structural strain monitoring

Fei Luo a,c,*, Jingyuan Liu b, Naibing Ma a, T.F. Morse c,1

a Department of Measurement and Test Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
b Department of Material Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
c Laboratory for Lightwave Technology, Division of Engineering, Brown University, Providence, RI 02912, USA

Received 16 April 1998; received in revised form 2 January 1999; accepted 6 January 1999

Abstract

A fiber optic microbend sensor with an elastic, arched sensing diaphragm has been developed for structural strain measurement. The combination of multiple microbend sensors can form a sensor array for the quasi-distributed sensing application in the monitoring of local strain or deformation along structures, and the optical time domain reflectometry can be conveniently used for interrogation of each sensor unit. The sensor sensitivity can be set at a specific value according to the requirements of the measurement condition. Connected with multiplexed sensing processing schemes, the sensor array may find an application in the real-time monitoring and damage detection of large and critical engineering structures. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Fiber optic microbend sensor; Distributed fiber optic sensor; Strain measurement

1. Introduction

For the on-line monitoring of large-scale engineering structures, developing Distributed Optical Fiber Sensors (DOFS) are of great interest [1,2]. The DOFSs can be used to satisfy many specific engineering demands, where there is a large number of continuously distributed parameters in the engineering structures that must be measured. The increasing interest in the DOFS is including the development of fiber optic smart structures [3].

Fiber optic microbend sensors [4] have the general advantages of fiber optic sensors. They are low-cost, reliable, simple, and they can be multiplexed for use in distributed sensing application. In many practical applications, microbend sensors have shown an ability to sense a variety of parameters. Microbend sensors have been successfully developed as displacement sensors, pressure sensors, acceleration sensors, and vibration (or acoustic) sensors [5]. There is also a particular interest in developing fiber optic microbend sensors for distributed sensing application [6–8]. In order to do this, it is an essential issue to build an effective structure of microbend sensors for transducing the certain measured parameters.

In the present paper, we develop a novel type of microbend sensor for strain measurements. The sensor can be mounted on the structures to sense strain or deformation. The sensitivity and dynamic range of the sensor may be adjusted to the requirements of measure and by choosing the proper parameters of the sensor. Our interest is to develop this microbend sensor to build a sensor array that will be connected to existing multiplexed processing schemes for the fiber optic sensors. Commercial Optical Time Domain Reflectometry (OTDR) is particularly convenient to use with a microbend sensor array. Each unit in the microbend sensor array can be conveniently interrogated with OTDR. Thus, local strain along the structure can be evaluated according to the local light loss measure-
ments at each sensor unit along the sensor array. A tempting prospect of the sensor system is that they can be used for on-line monitoring of the important engineering structures (such as bridges, dams, wells, submarines and space vehicles, etc.) for their security or their damage diagnosis and evaluation.

2. Configuration of the microbend sensor

The fiber optic microbend sensor is based on the phenomena of optical fiber microbend loss, where an optical fiber is placed between a pair of corrugated plates with teeth. When the lightwave propagates along the fiber, local light loss will occur at the bent region of the optical fiber due to the mode coupling between guided modes and radiation modes. The higher-order modes in a multimode optical fiber will be most easily coupled out from the fiber at small bends. The microbend loss of the fiber is a function of the fiber bending amplitude and its sinusoidal tooth spacing or mechanical wavelength.

To be presented here, we developed a novel structure of the microbend sensor for the strain measurement. The basic configuration of the sensor is illustrated in Fig. 1. The mechanical sensing element of the microbend strain sensor is an elastic, arched diaphragm with several teeth on it. Both ends of the diaphragm are fixed to the lower substrate of the sensor. The substrate of the sensor is firmly bonded to the structure to be interrogated, so that the substrate will be effected with the same strain action. The teeth on the substrate are matched with those of the arched diaphragm, as shown. The sensing optical fiber is located between the teeth. The microbend loss of the optical fiber will be a sensitive function of the sinusoidal bending amplitude on the fiber, which will be dependent on the gap in the teeth couple. Under the influence of longitudinal strain, the two ends of the elastic diaphragm will produce a relative displacement in the strain direction, so that the arch height of the diaphragm will be changed accordingly. Thus, the tooth gap will vary with the arch height change of the diaphragm that will cause a corresponding microbend modulation on the fiber and induce a loss of the fiber. The structural strain will be measured by monitoring the light power level of the output light from optical fiber.

Fig. 2 shows a key diagram of this microbend strain sensor. Assuming the variation of the arched elastic diaphragm is geometrical only, from Fig. 2, if the structural strain $\varepsilon$ is along the $x$-direction, we can represent the tooth gap change $\delta y$ in the microbend strain sensor ($y$-direction) as

$$\delta y = hx\varepsilon$$

where $h$ is a sensitivity factor for the sensor, and $k$ is the ratio of the arch height and the span of the sensor,

$$k = \frac{h}{2x}.$$

The relationship between $h$ and $k$ can be calculated from Eq. (2), as is shown in Fig. 3.

In this microbend strain sensor, the sensitivity of the strain measurement may be enhanced due to the magnification effect of the sensitivity factor $h$. Its sensitivity can be set up at an appropriate value or optimized point according to the measurement requirement by choosing parameter $k$ in Eq. (2).

3. The microbend sensor experiments

A practical sensor construction for the test is shown in Fig. 4, where the microbend sensor was designed to mea-

![Fig. 3. The relationship of $h$ depending on the parameter $k$.](image3)

![Fig. 4. A microbend sensor configuration for strain measurement testing.](image4)

![Fig. 5. The strain measuring tests with different microbend mechanical wavelength $\lambda$.](image5)
Fig. 6. The strain measuring tests with different corrugated bending periods of the fiber.

Fig. 8. Marked three measured regions along the sensing optical fiber.

sure the tensile strain of a test beam. The corrugated direction of the teeth couple in the microbend sensor was rotated 90\(^\circ\) where compared with Fig. 1, so that the sensing fiber can conveniently pass through the sensor teeth. The sensing diaphragm and substrate of the sensor were made of stainless steel. The sensor was bonded on a steel test beam. At the same time, a resistance strain gauge was installed on the surface of the test beam close to the microbend sensor in order to get a standard strain value. We can compare the light power level from the microbend sensor with the standard strain value. The following experiments show the test results for using a 50 \(\mu\)m/125 \(\mu\)m multimode optical fiber as sensing fiber. The span of the microbend sensor is 80 mm for these experiments. A computer-based data acquisition system was used to collect both of the measured light power output from the microbend sensor and the strain signal from the resistance strain gauge.

In the presented experiments, Figs. 5 and 6 show the monitored light power change percentages vs. the microstrain on the microbend sensor. In Fig. 5, the strain measuring tests were performed under different microbend mechanical wavelengths \(\Lambda\), where three corrugated bending periods were on the fiber. In Fig. 6, the spatial microbend mechanical wavelength of the fiber was chosen at \(\Lambda = 3.5\) mm; the experiments show the strain sensitivity under different corrugated bending periods of the fiber, where the microbend sensor has a different number of teeth. The output characteristics of the microbend sensor is dependent on the bent mechanical wavelength and the corrugated bending periods of the sensing fiber, that has been described more in detail by previous researches [6].

The above results indicate that there is sufficient flexibility to design an optimized microbend sensor according to practical measurement conditions. In the sensor components, at least, we can choose three parameters, the microbend mechanical wavelength, the corrugated bending periods (corresponding with the teeth number of the microbend sensor) and the sensitivity factor \(h\) in Eq. (2). The proper combination of the parameters in the sensor may lead the sensor to be used in most convenient for variety of circumstances.

Consequently, the microbend strain sensor has been tested for quasi-distributed sensing applications, where several microbend sensors were constructed in a sensor array along an optical fiber. The strain sensor array was attached on a measured structure as schematically shown in Fig. 7. The OTDR is used for locating each sensor unit and the local light loss occurring on each microbend sensor unit can be given according to the scanning output from backscattered light signal along the fiber. Because the change of the partial light loss on the fiber corresponds to the local strain on the sensor unit, the strain distribution caused by the structural deformation can be evaluated by summarizing the information at every sensor unit along the sensing fiber according to the OTDR’s output. A sensor array including three sensor units was arrayed on a test beam for proving the practical possibility of the distributed sensing application. The local strain along the test structure is marked as a function of position along the sensing fiber as shown in Fig. 8 by using OTDR system.

4. Conclusions

A novel fiber optic microbend sensor was developed for strain measurement. The sensor is simple in concept and inexpensive and can be optimized to meet a variety of design. The sensor could be conveniently used either as a point sensor or in distributed sensing applications, where the OTDR technique provides an effective method for realization of this quasi-distributed measurement. A tempting application will be in the on-line monitoring such as large engineering structures for their security or their damage diagnosis and evaluation.
Acknowledgements

This work was sponsored by the For Yingtung Education Foundation in Hongkong and the Aeronautical Science Foundation of China. Many thanks to Professor T.F. Morse, Laboratory for Lightwave Technology of Brown University, for his helpful discussion.

References


Fei Luo received his BS and MS degrees from the Hefei Polytechnic University in 1982 and 1987, and he received his PhD degree in 1991 from the Chongqing University, P.R.C. He was an associate professor at the Nanjing University of Aeronautics and Astronautics, Department of Measurement and Testing Engineering. Currently, he is a visiting associate professor in the Division of Engineering, Brown University, USA. His interests in recent years are in the fiber optic sensors and their applications. He has authored or co-authored over 30 papers and holds two patents related to fiber optic sensors.

Jingyuan Liu received her BS degree in materials engineering from the North-East University in 1986 and received her MS degree in metallurgy and materials engineering from the Chongqing University, P.R.C., in 1989. She is currently in the Department of Materials Science and Engineering at the Nanjing University of Aeronautics and Astronautics. Her researches in recent years are in the sensory materials and its applications.

Naibing Ma received his BS and MS degrees in Electronics Engineering from the Nanjing University of Aeronautics and Astronautics in 1991 and 1998, P.R.C. He is an assistant lecturer in the Department of Measurement and Test Engineering, Nanjing University of Aeronautics and Astronautics. His research work in recent years is in the fiber optic sensors.

T.F. Morse is a professor and director of the Laboratory for Lightwave Technology, Brown University, USA. His interests include the optical fiber laser and amplifier, fiber optic sensors and their applications, special optical fiber manufacture. He has authored or co-authored over 100 papers.