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Electric current measurement using fiber-optic curvature sensor

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ABSTRACT

A novel fiber-optic curvature sensor, which can measure curvature directly, has been developed in recent years. The electric current measurements system based on fiber-optic curvature sensor and electromagnetic principle is developed. A fiber-optic curvature sensor is bonded to a thin-walled cantilever and two circular magnet targets with the same parameters are configured at the tip of the cantilever symmetrically. In this case, the throughput of the sensor will be changed due to the bending deformation of cantilever, which is proportional to the electromagnetic force caused by measured electric current. Direct and alternate characteristics of the proposed measurement system are studied experimentally. The results show that the measurement errors are within the range of ± 5.5 mA and the corresponding accuracy is within 1% at the current measurement range from -300 mA to 300 mA, which indicate the feasibility of the proposed measurement system.

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1. Introduction

Strain gauges are often used to measure the stress or strain of structure surface, and then the curvature can be obtained through the functional relationship between strain and curvature. However, the strain gauges cannot be used to measure larger bending deformation; otherwise they will not return to their original shapes after stretching [1]. An inexpensive conductive ink sensor can detect the curvature [2]. However, its measurement range is limited to 0.01–0.1 mm^{-1}. In recent years, Fiber Bragg Grating and Long Period Fiber Grating have been used to measure bending deformation [3,4]. Optical interferometry has always been associated with precision metrology and they are also had been used to curvature measurement [5–7]. However, these complex systems require expensive devices. Based on the principle that the loss of light propagation will increase suddenly under big curvature, a fiber-optic sensor is proposed to monitor respiratory chest circumference [8,9]. Because the surface of fiber is untreated, the sensitivity of the sensor is very low and cannot distinguish the bending direction.

With the introduction of the fiber-optic curvature sensor reported recently [10–12], measurement of bending deformation has become easier and more practicable. As is well known, the sensitivity of untreated optical fibers is insufficient to detect the deformation of structures in bending. In order to increase the fiber's sensitivity to curvature, a sensitive zone is introduced on one side of the fiber by precision machining. The cutout produced removes a part of the fiber core and introduces a loss of light propagating along, as shown in Fig. 1 [13]. In [14], the three-dimensional analysis of light propagation through the fiber-optic curvature sensor is reported. The experimental optimization of the sensor has been presented in [15] and the operation principles of the sensor are shown in [16]. In [17] and [18], mathematical models of such sensor are presented. This kind of sensor is a light intensity modulation fiber optic sensor and has following characteristics [19–21]:

- It can directly measure curvature of structure and is only sensitive to curvature changes instead of strain and temperature.
- It is demonstrated that the throughput of the sensor varies linearly with deformation curvature when the deformation radius is above 60 mm.
- It demonstrates polarity. The sensor can distinguish between positive bending (sensitive zone is on the convex side) and negative bending (sensitive zone is on the concave side). Positive bending would decrease the throughput of light and conversely, negative bending would increase the throughput.
- It is small in size, simple in structure and low in cost. It is very easily made by multi-mode plastic optical fiber, and the detection equipments are very simple.
- It has better sensitivity. Compared to untreated fiber, fiber-optic curvature sensor is over 3 orders of magnitude more sensitive.

Fiber optical sensors used for electric current measurement have been widely discussed [22]. Many theoretical or experimental

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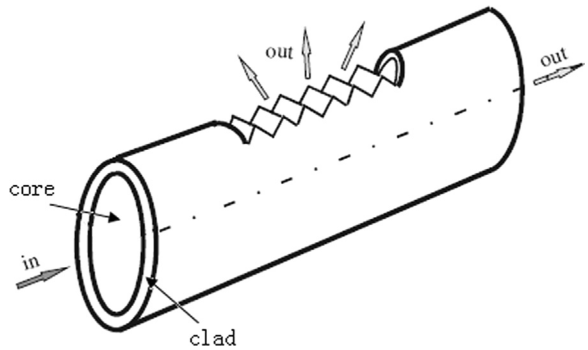

Fig. 1. A fiber with a sensitive zone [9].

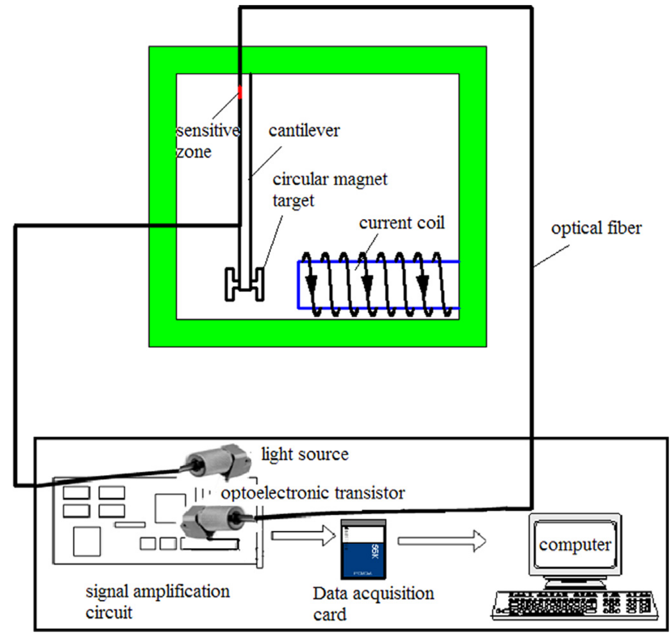

Fig. 2. Schematic diagram of current measurement system.

results of fiber optic current sensors have been obtained. Optical fibers based on all-fiber Mach–Zehnder interferometer have been utilized to measure electric current, in which the phases of interferometric lights in the interferometer is modulated by utilizing heat effect caused by current flowing through a thin metal tube [23]. Fiber optical sensors based on birefringence characteristics [24], multiplexed interferometric sensors [25] and fiber Fabry–Perot interferometer [26] are also been used to measure electric current. Electric current also can be measured by FBG sensors in the presence of some mechanical transducers [27]. However, most of the above electric current measurement methods need complex system or follow-up expensive analytical equipments. Besides, electric current measurement accuracy of some methods is influenced by external environmental factors, such as temperature.

Compared with the above electric current measurement method by fiber-optic sensors, in this paper, we report a sensing system to measure electric current based on fiber-optic curvature sensor and electromagnetic principle. Although the precision of the sensing system proposed in this paper is lower than FBG sensing system and interference technique, it has the unique advantages, including simple in structure, low in cost, immune to temperature and so on, which makes them a potential extensive application in the future.

Because the light signal can be transmitted easily by fiber for a long distance, the sensing system proposed in this paper is more suitable for remote current measurement compared with most existing commercial electric current measurement devices. However, the proposed measuring system is based on the electromagnetic principle, which makes the readout of measurement system is easily interfered by electromagnetic interference. That is to say, the external electromagnetic interference should be avoided in the process of electric current measurement.

2. Sensing system and principle

2.1. Sensing system

The schematic diagram of electric current measurements system based on fiber-optic curvature sensor is shown in Fig. 2. In Fig. 2, a fiber-optic curvature sensor is bonded to a thin-walled cantilever by flexible silica gel adhesive and the sensitive zone plane of the fiber-optic curvature sensor is parallel to the cantilever plane, which makes sure that the sensor has a maximum sensitivity when the cantilever is bending [19]. The sensitive zone is opposite of the cantilever. That is to say, the sensitive zone is not in contact with cantilever, which makes sure that the sensor is working on normal operating conditions and the light transmission in the optical fiber does not influence by cantilever. Two circular magnet targets with the same parameters are configured at the tip of the cantilever and they are on the opposite sides of the cantilever symmetrically. In this case, the weight is balance at two side of cantilever, which makes sure the cantilever is vertical and unbent at the initial status. When the measured electric current is input the coil, an electromagnetic force caused by current coil will act on the circular target, which pull or push the cantilever tip. In this case, the bending curvature of sensor is proportionate to the electromagnetic force. The curvature of cantilever can be obtained by detecting the throughput of the sensor. And then, the current of the coil can be obtained through the functional relationship among curvature of the cantilever, electromagnetic force and current of coil.

In the experiments, LED IF-E96-R was used as a light source and the corresponding receiver was optoelectronic transistor IF-D92. Data acquisition card PCL818L was used to collect the voltage signal. As polymer optical fiber is more flexibly than silica fiber and suitable for bending and connecting, the optical fiber used in this experimental setup is plastic optical fiber with a diameter of 0.25 mm and the numerical aperture of 0.51, which is made by Mitsubishi Company. In [18], we have given an optimization of this kind of optical fiber. According to optimization results, the parameters configuration of depth, height and the number of tooth are 90 μm, 30 μm and 50 respectively. When the procedure of fiber-optic curvature sensor fabrication is at these value levels, the maximal sensitivity of sensor can be obtained.

The position of the measurement system is fixed, including the part of the fiber lead-in and lead-out lengths, the light source and the photo-detector. That is to say, the part of the fiber which connecting the sensor to the light source and to the photo-detector is static in the process of electric current measurement, which can reduce the effect of fiber itself on the measurement results.

2.2. Sensing principle

On the assumption that the density heterogeneity of the cantilever could be ignored, when the measured current is input into the coil, an electromagnetic force will occur perpendicular to the cantilever, resulting in the deformation of the cantilever. The relationship between electromagnetic force (F) acting on the

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