第 20 卷　第 8 期
2000 年 8 月

光　学　学　报
ACTA OPTICA SINICA

Vol. 20, No. 8
August, 2000

Embedded Fiber Optic Sensors for Detection of Acoustic Emissions in Structures

Chen Zhongyu*　　Farhad Ansari

(Smart Sensors & NDT Laboratory, New Jersey Institute of Technology, Newark, NJ 07102, USA)

Abstract Acoustic emission (AE) technique has been applied to metallic and concrete structures as a nondestructive testing (NDT) method for detection of internal cracks. Current techniques employ PZT transducers for acquisition of AE signal. The work presented here describes development and testing of an AE sensor based on the optical fiber technology. It can monitor the crack signal in the concrete structure, for example, bridge, highway, tunnel and building etc., using the embedded optical fiber sensor.

Key words acoustic emission, optical fiber sensor, nondestructive testing.

1 Introduction

Internal damage events such as evolution of micro-cracks give rise to acoustic emission signals in materials. Many researchers have used the acoustic emission technology for nondestructive detection of internal cracks in structural elements[1]. Acoustic emission signals are very weak and require sensitive transducers. For this reason, piezoelectric sensors have been primarily employed for detection of acoustic emission signals[2, 3].

The work described here presents development of a new class of acoustic emission sensors based on the fiber optic technology. Optic fibers can be either embedded inside or adhered to the surface of structural elements[4]. Piezoelectric transducers (PZT) are point sensors and therefore they are not practical for condition monitoring of large structures. These sensors are suited for situations where only a small segment of the structure needs to be interrogated i. e. welded connections, etc. Optical fibers are capable of making distributed measurements over the entire length of a structure and thus suitable for NDT of large structures[5]. The development of an optical fiber acoustic emission sensor is described in the article and some preliminary results are presented.

* Permenent address: Shanghai Institute of Optics and Fine Mechanics, The Chinese Academy of Sciences, Shanghai 201800, China.

Received 29 October 1999; revised 4 January 2000

2 Fiber Optic Sensors for Acoustic Emission Analysis

When optical fiber is subjected by the mechanical stress of radial (axial), the length of optical fiber (strain effect), diameter of optical fiber core (Poisson effect), the refraction index of optical fiber core (photoelastic effect) will be changed, this changes will cause the variety of optical wave phase. The sound wave detection uses the photoelastic effect.

Most conventional sensor for the detection of sound waves is piezoelectric elements. They are attached to the host material directly or through a mechanical support housing assembly. Oscillatory particle displacements associated with wave motion strain the transducer element, producing an output voltage that may be interpreted in terms of displacement amplitudes. In our experiment, we employed a straight optical fiber, a coil optical fiber and a series of coils optic fiber as sensor separately.

Particle motion associated with acoustic wave is elliptical retrograde with respect to the direction of propagation and decays as a function of distance away. The wave motion may be modeled as being composed of instantaneous orthogonal displacement components oriented parallel and normal to the surface of material. The shape of the ellipse and the decay depend on the acoustic frequency, density and moduli of the material. Thus the measurement of one of the displacement components allows evaluation of the entire surface acoustic wave field[6].

Although the sound stress wave fields are generated by the phenomena such as acoustic emission events in material. Alternatively both direct and indirect in-line methods may be used to detect acoustic waves which perturb light propagating in a fiber or fiber sensor assembly attached to or embedded in a material that supports an elastic wave. Several conventional interferometric configurations in particular may be used to detect acoustic emission wave with gauge lengths that are generally large with respect to the acoustic wavelength. Short gauge-length interferometric-based detection methods (for example F-P fiber optical sensor), however, offer performance comparable, in their compact and low-profile surface geometry, and superior in minimum-detectable displacement-piezoelectric element.

3 Fiber Optical Interferometry Theory for Acoustic Emission Measurement

In optical fiber, the phase of light wave is decided by physical length change of optical fiber waveguide, index change of refraction and its distribution, geometry size change of the crosswise of waveguide. In general, for those such as the ultrasonic wave etc., their external physical values will directly change above some waveguide parameters. But now a lot of optical detectors do not detect the change of optical phase, so it must adopt optical interference technology to transfer them from the phase change to optical intensity change. So we will employ optical interferometer, and this kind of interferometer has very high sensitivity.

The theory of operation for optical fiber interferometers is essentially the same regardless of geometry. The delay in the optical phase measured through a single-mode optical fiber is

$$\varphi = nkl, \tag{1}$$

where n is the index of refraction of the core of the fiber, k is the optical wave number in vacuum, and l

is the length of the fiber over which the phase delay is measured. A small change in this phase delay which may occur at some position along the length of the fiber may be expressed to the first order as

$$\frac{\delta\varphi}{\varphi} = \frac{\delta l}{l} + \frac{\delta n}{n} + \frac{\delta k}{k}. \tag{2}$$

such a change may be associated with effects internal to the fiber for intrinsic sensors, in which light remains within the fiber waveguide all along its length, or external to the fiber for extrinsic sensor, in which light exits the fiber at some point along its length, interacts with the local environment, then reenters the waveguide and is transmited to detection circuitry. Several types of extrinsic and intrinsic fiber sensors have been used to monitor acoustic wave motion on materials. It should be noted that the gauge length of the sensor for intrinsic sensors is a length of fiber, in the object to be measured. For the measurement of the local high-frequency stress wave field associated with acoustic wave propagation, for example, cross terms such as

$$\frac{\delta n}{n\delta'} \qquad \frac{\delta k}{k\delta'} \tag{3}$$

would appear in equation above in the case of intrinsic sensor operation due to the modulation of the index of refraction of the glass in the core of the fiber due to the photoelastic effect that occurs when the fiber is strained, and the change that occurs in the propagation constants due to the strain-induced deformation of the waveguide. Extrinsic sensor avoids such first-order cross-sensitivity problems for small changes in strain, or similarly in temperature, due to the relative insensitivity of air to external modulation effects.

4 Sensor Methodology

Stress waves that are generated in materials by way of acoustic emission perturb the light propagating though the embedded or adhered optical fiber. Interrogation of this perturbed light is used for nondestructive evaluation of acoustic emissions within a gauge length of the optical fiber. The theory of operation for optical fiber interferometers pertains to the measurement of the phase delay due to induced mechanical perturbations. In a Michelson interferometer two optical fibers are used as reference and sensor arms of the interferometer. Through the coupler, two reflected signals are recombined into APD, if their optical path difference falls within the coherent length of the light (from the light emitting diode), a white light fringe patterns is produced. The acoustic emissions modulate the phase shift in the perturbed signal. The experimental arrangement for the acoustic emission interferometer system is shown in Fig. 1. A high-speed photo-detector, as well as a narrow band filter, and a high gain amplifier were used to direct the signal to a digitizing oscilloscope. At this point data is transferred to a computer for analysis and storage. The transient data is prone to low frequency drift. A low-frequency feedback control system is used for maintaining the output of the interferometer at the quadrature point.

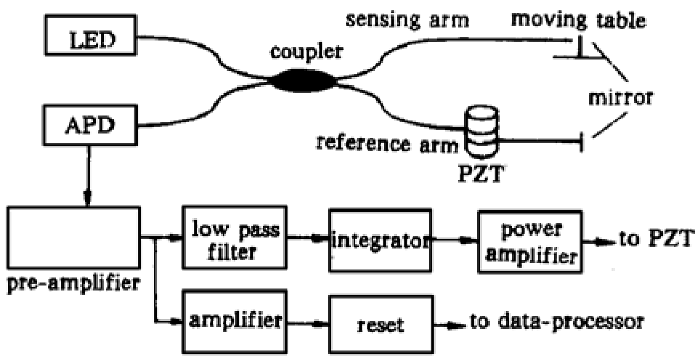

Fig. 1 Experimental setup for the optical fiber acoustic emission sensor. APD stands for avalanche photo-diode

5 Experimental Results

Evaluation of the optical fiber sensor was accomplished through the experimental arrangement shown in Fig. 2. The optical fiber sensor was embedded in a center notched three-point-bend specimen. A conventional PZT sensor was adhered to the surface of the specimen for comparison. The experiment was conducted under closed loop displacement control. An line voltage-displacement transducer (LVDT) was employed for measuring the crack mouth opening displacement (COD). The COD signal was used as the feedback signal for the close loop system.

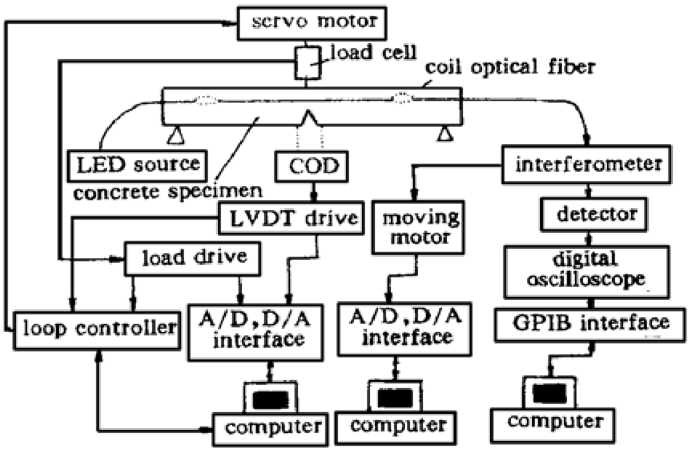

Fig. 2 Experiment setup for testing the single edge notched concrete beam. GPIB stands for General Purpose Interface Bus

Fig. 3 corresponds to the load-displacement data for the concrete beam.

Micro-cracking and crack progression events detected by the optical fiber and the PZT sensor are shown in Fig. 4. The optical fiber is able to detect the micro-cracking of concrete prior to the peak load. Furthermore, the sensor is able to continuously monitor the progression of crack after the peak load.

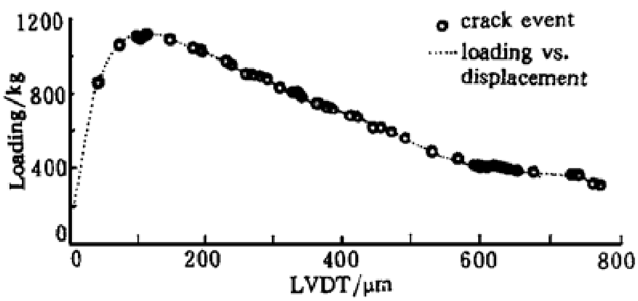

Fig. 3 Load displacement curve for the concrete specimen and the acoustic emission events

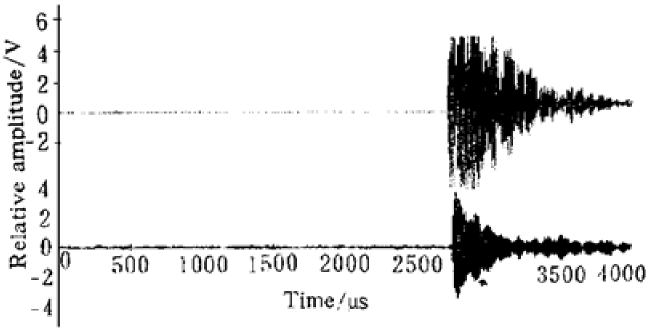

Fig. 4 Comparison of the acoustic emission signals detected by PZT transducer (upper), detected by fiber optical sensor (lower)

Conclusion Development and performance of an acoustic emission sensor based on an optical fiber interferometer is described. The system was evaluated through experiment with concrete samples. Results are compared with data acquired from conventional PZT sensors. Both types of sensors are able to detect the acoustic emission events.

Acknowledgements This work was made possible by a grant from the National Science Foundation, grant number CMS-9402671, to the New Jersey Institute of Technology.

References

[1] Ouyang C, Landis E, Shah S P. Damage assessment in concrete using acoustic emission. In: *Nondestructive Testing of concrete Elements and Structures*. Ansari F. ed., New York: ASCE-EMD, special publication, 1992. 1324

[2] Ohtsu M. Determination of crack orientation by acoustic emission. *Materials Evaluation*, 1986, **45**(10): 10701075

[3] Scruby C B, Baldwin G R, Stacey K A. Characterization of fatigue crack extension by quantitative acoustic emission. *Int. J. Fracture*, 1985, **28**(3): 201222

[4] Ansari F. State-of the art in the applications of fiber optic sensors to cementitions composites. *Cement and Concrete Composites*, 1997, **19**(1): 623

[5] Ansari F. Theory and applications of integrated fiber optic sensors in structures. In: *Nondestructive Testing of concrete Elements and Structures*. Ansari F. ed., New York: ASCE-EMD, special publication, 1997. 228

[6] Ohtsu M, Shigeishi M, Iwase H *et al*.. Determination of crack location, type and orientation in concrete structures by aconstic emission. *Magazine of Concrete Research*, 1991, **43**(155): 127134

用埋入式光纤传感器探测建筑结构中的声发射

陈仲裕 Farhad Ansari

(新泽西理工大学, 灵巧传感器和无损检测实验室, 美国 纽瓦克 NJ 07102)

(收稿日期: 1999-10-29; 收到修改稿日期: 2000-01-04)

摘 要 声发射技术已经应用于金属和混凝土结构中, 作为探测内部裂缝的一种无损检测方法。目前用的技术都是由压电换能器来采集声发射信号。讨论了基于用光纤技术的声发射传感器的开发和测量方法。它是用埋入式光纤传感器来监测类似桥梁、高速公路、隧道和房屋建筑等混凝土结构中的开裂信号。

关键词 声发射, 光纤传感器, 无损检测。