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Prediction of Situations That May Occur in Emergency Situations of Bridges by Means of Optical Sensors

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Annotation

In recent years, with the development of materials science and architectural art, ensuring the safety of modern buildings is the top priority while they are developing toward higher, lighter, and more unique trends. Structural health monitoring (SHM) is currently an extremely effective and vital safeguard measure. Because of the fiber-optic sensor's (FOS) inherent distinctive advantages (such as small size, lightweight, immunity to electromagnetic interference (EMI) and corrosion, and embedding capability), a significant number of innovative sensing systems have been exploited in the civil engineering for SHM used in projects (including buildings, bridges, tunnels, etc.). The purpose of this review article is devoted to presenting a summary of the basic principles of various fiber-optic sensors, classification and principles of FOS, typical and functional fiber-optic sensors (FOSs), and the practical application status of the FOS technology in SHM of civil infrastructure.

Keywords: fiber-optic sensors; structural health monitoring; distributed fiber-optic sensor; optical time-domain reflectometer; civil engineering

Introduction. Modern large-scale civil engineering such as bridges, tunnels, space shuttles, large dams, and other infrastructure facilities have significant applications. These facilities not only require huge economic investment in the manufacturing process but also are closely related to personal safety. The facilities' service life is usually decades or even hundreds of years [1,2]. In the course of using, they could inevitably be coupled with various disasters (such as environmental loads, fatigue effects, etc.). The structure could appear in different degrees and different kinds of damage [3,4], which may cause serious personal accidents and property losses. Therefore, whether these structures can work safely for a long time has attracted lots of attention. It is necessary to carry out real-time health monitoring and evaluation of engineering structures to put an end to the potential hazards and improve the safety performance of civil facilities.

Real-time SHM for major engineering structures can timely identify the cumulative damage of the structure and evaluate its service performance and life, and establish a corresponding safety early warning mechanism for early warning of possible disasters, which is not only of great scientific significance for improving the safety and reliability of the structure, but also can reduce the cost of operation and maintenance of the structure. It has become the inevitable requirement of the future engineering, and also a tough issue to be solved urgently [5,6,7].

SHM is an important application of intelligent material structure in practical engineering, which can monitor the "health" state of the structure on-line. It uses embedded or surface-bonded sensors as the nervous system to sense and predict internal defects and damage in the structure. The overall and local deformation, corrosion, brace failure, and other factors of the structure can be evaluated by the SHM system. When there is a sudden accident or dangerous environment, it can restore the whole structural system to the best working state through adjustment and control. Of course, the structure can protect itself and survive in times of danger by automatically changing and adjusting the shape, position, strength, stiffness, damping or vibration frequency of the structure.

Classification and Principles of Fiber-Optic Sensor (FOS). The working process of the optical fiber sensor includes but not limited to the monitoring of external factors and signal transmission. When light propagates in an optical fiber, characteristic parameters such as light intensity, phase, polarization state, wavelength, or frequency will change. Therefore, FOS can be divided into intensity-modulated FOS, phase modulated FOS, polarization modulated FOS, and frequency modulated FOS. In the FOS system,

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the modulation occurs inside the optical fiber when the light in the optical fiber is transmitted from the light source to the detector, called the intrinsic FOS. The modulation that occurs outside the optical fiber called extrinsic FOS. FOS can be divided into interferential FOS and non-interferential FOS according to whether the light interferes or not. In addition, according to the induction range, FOS can be divided into point (local) FOS, quasi-distributed FOS, and distributed FOS. The most commonly used in civil infrastructure are Fabry–Perot fiber-optic sensor (FPFOS) [8,9], fiber Bragg grating (FBG) sensor [10,11], optical time domain reflectometer (OTDR) [12,13], and long-period fiber grating (LPFG) sensor [13,14].

Fabry–Perot Fiber-Optic Sensor. The optical fiber sensors utilize the change of optical phase affected by the physical field to reflect the properties of the measured objects. After being emitted by the light source, the light is divided into two beams with the same frequency, polarization direction, and initial phase through the prism. One beam is signal light and the other beam is reference light. Interference occurs when they meet. The interference image can be used to infer the influence of external factors on the signal light. Interferometric FOS can be divided into Michelson FOS, Mach-Zehnder FOS, Sagnac FOS, and Fabry–Perot FOS. The schematic diagram of the Fabry–Perot interference cavity is shown in Figure 1. We mainly introduce the FPFOS in this review.

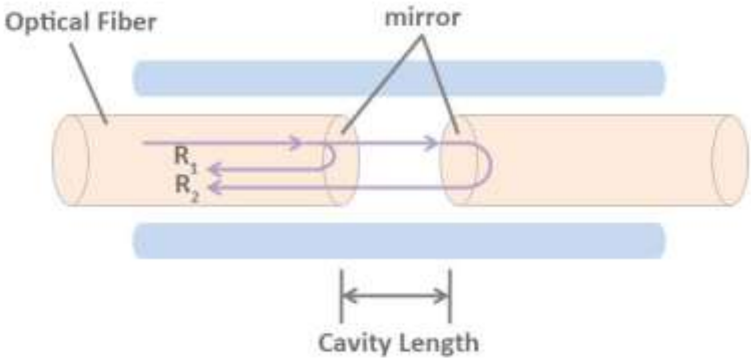

Figure 1. Schematic diagram of Fabry–Perot interference cavity.

The core of the FPFOS is the interference cavity. According to the different structure of interference cavity, FPFOS can be divided into intrinsic type and non-intrinsic type. In the intrinsic Fabry–Perot interferometric (IFPI) sensing system, the interference cavity is generally composed of a single-mode fiber-optic and an insulated mirror, and the end face of the fiber-optic cut by the fiber-optic can also be used as a mirror. In the extrinsic Fabry–Perot interferometric (EFPI) sensing system, the interference cavity is composed of air or other non-fiber optic solid media. The light source can use either a He-Ne laser or a low coherence light source to form interference after entering the optical Fabry–Perot cavity. The above two types of Fabry–Perot FOSs make use of the physical parameters to be measured to cause the change of phase difference, so that the optical path difference is changed, and then the interference signal through the detector is transformed into electrical signal for processing. According to the change of coherent optical phase difference, the change of physical parameters to be measured can be obtained.

Fiber Bragg Grating Sensor. SHM is the most active field in the application of FBG sensors. The low manufacturing cost, high-quality demodulation system, and practical packaging technology are important factors for the wide application of FBG sensors. FBG sensors can be attached to the surface of the structure or embedded in the structure to achieve real-time monitoring of the structure and monitor the formation of structural defects. Besides, a large number of FBG sensors can be connected in series to form a sensor network system, and the sensing signals can be remotely accessed to the central monitoring room for analysis and processing.

At present, the FBG sensor has become a commonly used sensor in the field of grating sensing [12]. The structure and principles of FBG are illustrated in Figure-2. When the broadband light source passes through the fiber grating, the narrowband spectrum is reflected.

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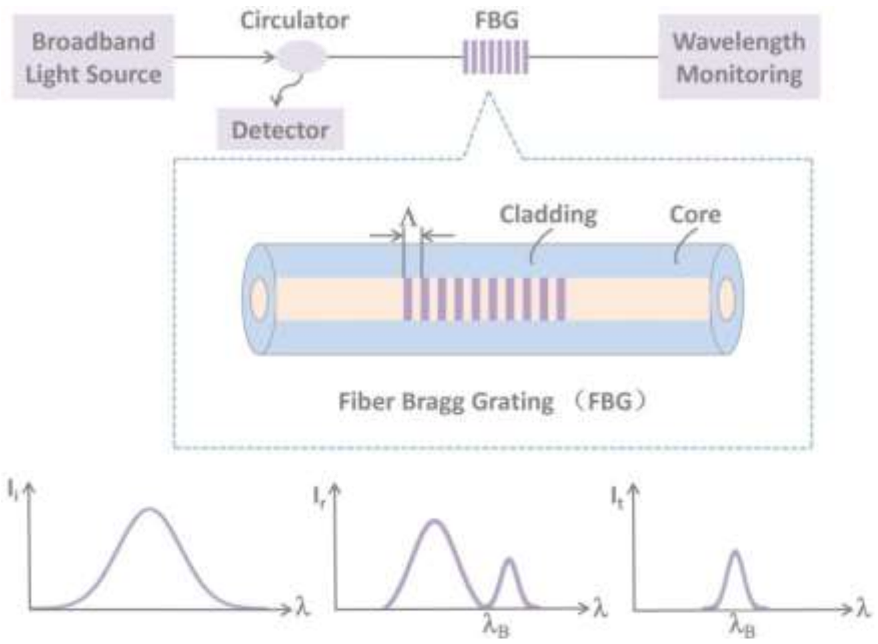

Figure 2. The principles and wavelength shift of fiber Bragg grating (FBG) sensors.

One of the most important FBG sensors is the quasi-distributed FOS based on FBG. Quasi-distributed FBG sensors use signal transmission fibers to connect multiple fibers or sensors together, and use the principle of multiplexing to separate the optical signals of different sensors, so as to analyze the monitoring data of different sensors. There is no need to lay the transmission fiber separately at each monitoring point compared with vibrating wire and resistive sensors, which makes engineering monitoring more convenient, low-cost, and efficient. Therefore, the multiplexed quasi-distributed FBG sensor is more suitable for monitoring crucial parts of large structures (such as pipelines, bridges, and dams), achieving multi-parameter measurement [13].

The wavelength signal of fiber grating sensor contains both temperature and strain information. To separate temperature information and strain information is a crucial issue in fiber grating sensor technology. Since 1993, people have been dedicated to studying the cross-sensitivity of fiber grating, many scholars have put forward numerous solutions. These solutions can be classified into: dual-wavelength transmission, dual-parameter method, temperature (strain) compensation method, fiber grating method with special performance, etc. In 2011, Stefani and Alessio proposed a method for temperature compensation using adjacent gratings to the strain sensor, and gave a method for writing multiplexed gratings. In 2013, Ping Lu used the high-sensitivity outer layer mode to achieve temperature and axial strain compensation. In 2014, Yiping Wang improved the cavity length of FPI through repeated arc discharge to reshape the cavity, reducing the cross-sensitivity between tensile strain and temperature. In fact, in order to resolve the crosstalk between strain and temperature to distinguish the strain, temperature compensation is performed. Assuming that the two sensors would experience the same temperature change, a separate distributed temperature sensor is installed near the strain sensor. This makes the fiber strain-free and only sensitive to temperature.

Optical Time-Domain Reflectometer *(OTDR).* The optical time-domain reflectometer (OTDR) uses the backscattered light of the fiber-optic to feedback the performance of the fiber-optic [14]. After the optical pulse emitted by the laser is injected into the fiber, the light energy received at the starting port can be divided into two types: (1) Fresnel reflected light of the fiber fracture surface or connection interface; (2) Rayleigh scattered light. As shown in Figure 3, the detected backscattered light power returned at various points along the length of the fiber contains information about the loss suffered when the light is transmitted along with the fiber, so that the attenuation of the fiber can be analyzed and determined. With OTDR, we can measure the attenuation of the fiber, check the continuity of light, physical defects, or the location of the break, even measure the loss and position of the joint, and measure the length of the fiber. The

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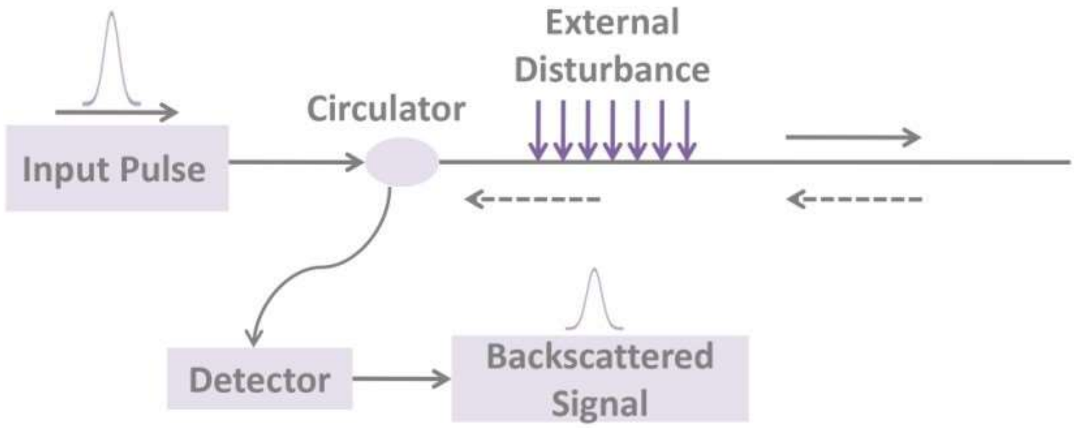
Brillouin optical time-domain reflectometer (BOTDR) sensor is a classic classification of the FOSs and is based on the Brillouin scattering. Brillouin scattering is affected by temperature and strain, and the Brillouin spectrum produces frequency drift, which leads to stretching or compression in the axial direction of the



fiber-optic. Therefore, the temperature and strain of the entire fiber can be obtained by calculating the frequency shift of the Brillouin backscattered light. OTDR unique single-ended monitoring technology has been widely applied in distributed monitoring of large-scale civil structures.

Figure 3. The principle of optical time-domain reflectometer (OTDR) based on backscattering.

Long-Period Fiber Grating (LPFG) Sensor. Long-period fiber grating (LPFG) is a novel type of optical fiber passive device that has appeared in recent years, which forms a periodic or aperiodic distribution of refractive index in the fiber core. Because of the coupling effect of the internal field, the LPFG would reflect or transmit light of a specific wavelength. The long period of LPFG makes its resonance wavelength and amplitude extremely sensitive to ambient temperature, strain, bending, and torsion. Moreover, LPFG is a transmission type fiber grating with no backscatter and high measurement accuracy. Therefore, it plays an increasingly essential role in optical fiber sensing.

The LPFG couples the fundamental mode energy of the core to the cladding mode transmitted in the same direction.

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