Full distributed fiber optical sensor for intrusion detection in application to buried pipelines

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Based on the microbend effect of optical fiber, a distributed sensor for real-time continuous monitoring of intrusion in application to buried pipelines is proposed. The sensing element is a long cable with a special structure made up of an elastic polymer wire, an optical fiber, and a metal wire. The damage point is located with an embedded optical time domain reflectometry (OTDR) instrument. The intrusion types can be indicated by the amplitude of output voltage. Experimental results show that the detection system can alarm adequately under abnormal load and can locate the intrusion point within 22.4 m for distance of 3.023 km.

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Distributed fiber optical sensors are based on the principle that the light intensity through optical fibers is sensitive to exerted pressure, stress, temperature, or contacted chemical substances, etc.. Changes of light transmission in the fiber may be detected by photodiode and the disturbed point can be located with the optical time domain reflectometry (OTDR) technology. In applications of damage monitoring for gas or oil pipelines, many optical fiber distributed sensing systems based on different principles have been studied[1−5]. These sensors have many advantages including real-time continuous monitoring, more than tens of miles detection for one sensing element, ability to detect and locate damage points along pipeline and immunity to electromagnetic interference, etc.[6]. However, most of these sensors are limited by high cost, complexity of instrumentation and signal processing, and difficulty in discrimination between benign and harmful events in practical applications. With the developments of oil and gas transportations, many buried pipelines have been laid in urban and suburban areas, and the possibility of intrusions by unauthorized digging or drilling devices becomes increased. Therefore, low cost, easily installed sensing systems for intrusion detection need to be developed to guarantee the safety and reliability of pipelines. In this paper, a microbend-based full distributed fiber optical sensor used to detect and locate the potential intrusion before oil or gas leakage is designed and tested.

Figure 1 shows the system setup of the distributed fiber optical sensor. The light emitted from the laser diode is injected into the optical sensor through an opto-coupler. When certain abnormal load, such as caused by construction equipments, exerts on the fiber, the sensing cable, i.e., the modulated structure, will cause the microbend of optical fiber. The light intensity transmitted through the fiber will be changed and converted into output voltage by the photodiode and signal processing circuits. According to the preset criteria, which may be established through field experiments, different types of intrusions may be distinguished from the amplitude of output voltage. Furthermore, the location of harmful events may be determined by an OTDR instrument.

To implement distributed sensing, a type of sensing element with special structure has been developed. The sensor is a long continuous cable and composed of an elastic polymer wire, an optical fiber and a metal wire, as shown in Fig. 2(a). The polymer and the fiber are configured in parallel and are helically wounded by the metal wire[2]. The wounded period is 10 mm, which is determined by trial and error. When external load is applied on the cable, the metal wire, which acts as a line of "hard teeth", is indented into the elastic polymer wire and causes the microbend of optical fiber. This principle can be explained by the microbend modulator shown in Fig. 2(b).

According to optical wave theory, the light intensity attenuation coefficient due to microbend of fiber can be deduced as[6]

$$\alpha \approx \frac{1}{4} K D^2(t) L \left| \frac{\sin[(q-\Delta\beta)L/2]}{(q-\Delta\beta)L/2} \right|^2, \quad (1)$$

where K is a constant, $D(t)$ is magnitude of microbend, L is length of sensing optical fiber, q is frequency of tooth spacing, and $\Delta\beta$ is the propagation constant difference between adjacent propagated modes.

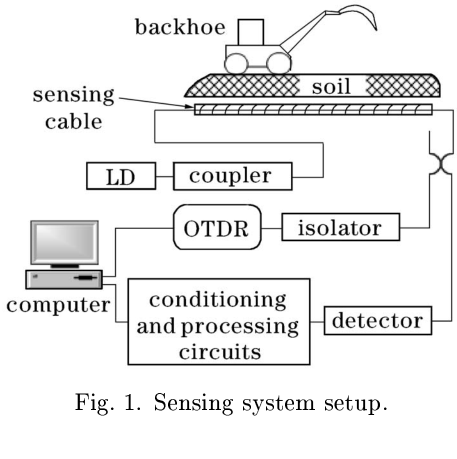

Fig. 1. Sensing system setup.

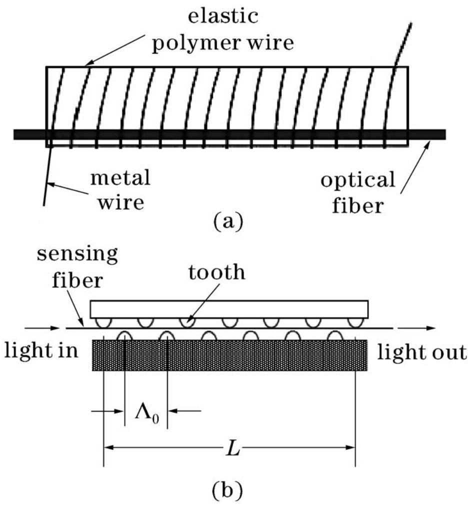

Fig. 2. Schematic diagram of sensing cable (a) and microbend principle (b).

It can be seen from Eq. (1) that the light intensity attenuation coefficient depends on $D(t)$, L, and q. $D(t)$ is dominated by measurands, L is dominated by the fiber length just between tooth pates, and q is dominated by period of the tooth spacing.

In a multimode fiber, the higher-order modes are those modes that are most easily coupled out of the fiber at small bends. Therefore the critical mechanical periodicity (see Fig. 2(b)) for graded index multimode glass fibers can be deduced as

$$\Lambda_0 = \sqrt{2}\pi a/\Delta^{1/2}, \tag{2}$$

where a is the fiber core radius, Δ is the normalized index difference between core and clad, $\Delta = (n_1 - n_2)/n_2$.

In order to locate the intrusion point along the optical fiber, a commercially low cost simple OTDR instrument was modified to be embedded in the developed sensing system. Also, a professional OTDR (AQ7250) was used to evaluate the performance of the system.

The basic OTDR technique is capable of detecting loss of light intensity as a function of position along a fiber[7] and locating some imperfections in fibers. As shown in Fig. 3, a light pulse is injected into the fiber and the photodiode detects the backscattered light energy. Through signal processing circuits, the relationship between light intensity loss and the distance can be obtained according to the time difference between incident and received pulses. When load applied on the fiber optical sensor, the fiber will be bended and thus an abnormal loss occurs. On the curve of loss versus distance, a sharp drop can be seen as the lower arrow points out.

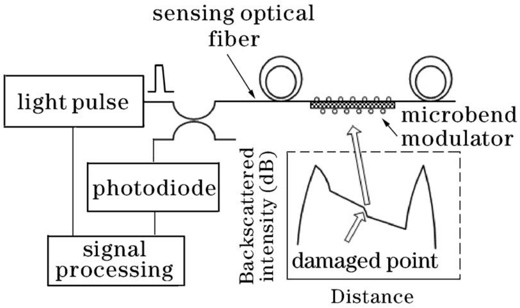

Fig. 3. Principle of OTDR.

The power $P(z)$ received at the input end of the fiber from a position along the optical fiber is given by[4]

$$P(z) = 0.5V_g \cdot S \cdot f \cdot c \cdot \Delta t \cdot P(0)\exp(-2\delta z), \tag{3}$$

where V_g is the velocity of the light pulse within optical fiber, S is the light-scattering coefficient, f is the fraction of scattered light which is the function of refractive indices of both fiber core and cladding, c is the coupling efficiency of optics, $P(0)$ is the optical output power of the laser, Δt is the pulse width of laser, δ is the total fiber attenuation caused by scattering and absorption effects in the fiber, and z is the position along the fiber.

The distance z from the input end of the optical fiber to the disturbed position can be given by[4]

$$z = \frac{V_g \cdot \tau_d}{2}, \tag{4}$$

where τ_d is the time delay between the light pulse entering the fiber and the response signal of the disturbed point.

The experimental setup is shown in Fig. 4. To test the performance of the distributed sensor, a 1.2-m length of sensing cable is welded together with two sections of long optical fiber on two ends. The total length of fiber (including the 1.2-m sensing cable used to be tested) is 3.023 km, which is obtained by a commercial OTDR (AQ7250).

A standard light-emitting module for optical communication was used as the light source. The PIN photodiode and the processing circuits convert the variation of light intensity into output voltage. To locate intrusion site,

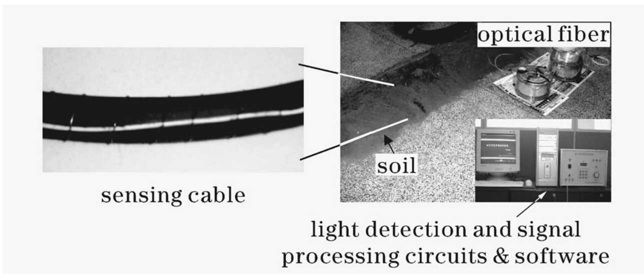

Fig. 4. Experimental setup for the test of distributed fiber optical sensor.

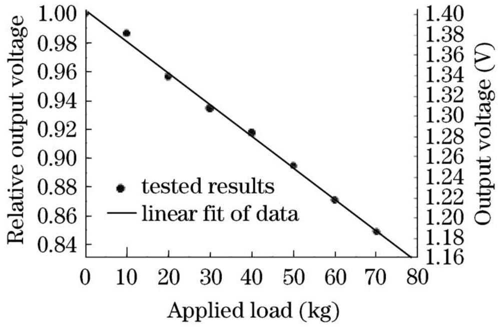

Fig. 5. Curve of output voltage versus applied load.

Table 1. Location Test of Intrusion Point

Equipment	Commercial OTDR (AQ7250)	Developed Distributed Fiber Optical Sensor						
		1st	2nd	3rd	4th	5th	Mean	Max Deviation
Tested Intrusion Location (m)	1728	1706	1706	1704	1708	1704	1705.6	−22.4

a simple commercial OTDR instrument was embedded into the system. The monitoring software is developed with Visual Basic.

The tested fiber cable was buried under soft soil in depth of 20 cm. Although the actual depth should be larger in field applications, it is convenient for the preliminary performance evaluation of the sensor. To test the relationship between the amplitude of output voltage and exerted load, wooden boxes filled with sand were placed in sequence on the soil just above the sensing cable. From the monitoring screen, the value of output voltage is recorded. Figure 5 shows the curve of relative output voltage (as well as the actual output voltage) versus load.

It can be seen that the output voltage decreases significantly with the increase of the applied load. The calculated sensitivity is 3 mV/kg for the sensing system. Because different third-party intrusions exhibit different loads on the sensor, it is possible to distinguish the type of potential damage from the amplitude of output voltage by comparing that with the preset load "fingerprint".

When the load is applied to the sensing cable and the output voltage decreases to an approximately stable value, the location, which is denoted with the distance between intrusion point and the light incident end of optical fiber, is obtained with both commercial OTDR (AQ7250) and the embedded simple OTDR instrument. Test was conducted five times for one intrusion point with the developed sensing system. Test results under the load of 50 kg are shown in Table 1.

Obviously, the performance of the sensor locating system works well. The maximum deviation between mean distance measured with the developed instrument and the value obtained from the commercial OTDR is 22.4 m, which is about the length of two pipe sections (about 12 m for each). The experimental results are very attractive for integrity management of oil and gas pipelines. In addition, the optical attenuation in non-flawed sections of the fiber is very small and the signal-to-noise ratio decreases very slowly with the increase of the distance. It is expected that very long distance of pipeline can be monitored with high location precision.

The developed full distributed fiber optical sensor system is very suited to be used in either long pipelines or branch-pipelines in suburban and urban areas to monitor the potential intrusion of third-party in order to alarm and locate the intrusion point before severe leakages occur to guarantee the safety and reliability of buried pipelines.

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