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A lateral locating method for optical fiber distributed intrusion sensing system

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ABSTRACT

A lateral locating method is proposed and demonstrated in optical fiber distributed vibration sensing system based on phase-sensitive optical time domain reflectometer. The locating depends on a method of time difference of arrival to calculate the time difference between two sensing points. Through this method, we can get the vertical distance between the vibration source and the sensing fiber. Therefore, we can make sure the degree of danger of intrusion. The test results show that the locating accuracy is about 2.10 m with 100-MHz sampling rate, 1-kHz pulse repetition rate, and 1500 sampling points within one pulse interval.

1. Introduction

Optical fiber distributed vibration sensors have attracted much research interests in recent years. It has advantages of high sensitivity, long distance monitoring, no power supply and accurate location, which provide the availability of intruder detection, early warning and location in the pipeline security monitoring system as well as power cable security monitoring system. Nowadays, most distinguished techniques for optical fiber distributed vibration sensing involve the optical fiber interferometer sensors and optical backscattering based sensors theoretically.

For optical fiber interferometer sensors, whichever is based on Mach–Zehnder interferometer [1,2], Sagnac interferometer [3,4] or Michelson interferometer [5,6] architectures, they are easily affected by environmental factors, and it is difficult to distinguish the rapid and slow interference, so they are unsuitable for long distance monitoring. A distributed fiber-optic vibration sensor based on a non-balanced Mach–Zehnder interferometer has been discussed [1] with the delay fiber of 25 km and the sensing fiber of 10 km. A simple configuration of a polarization maintaining (PM) fiber Sagnac interferometer [4] vibration sensor with a light emitting diode was proposed. Using this system, stable vibration sensing was successfully demonstrated with 1-kHz measurement frequency and 10-μW input power. And also, a highly stabilized vibration-displacement measurement system is reported, which employs fiber Bragg gratings (FBGs) to interleave two fiber Michelson interferometers [5] that share the common-interferometric-optical path. This measurement system is able to measure vibration with the frequency range from 0.1 to 200 Hz.

On the other hand, vibration measurement based on phase-sensitive optical time domain reflectometer (Phase-OTDR) [7,8], polarization optical time domain reflectometer (P-OTDR) [9] and Brillouin optical time domain reflectometer (B-OTDR) [10] are demonstrated. In [7], modulated pulses based on the distributed vibration sensing method by merging interferometer and Phase-OTDR are proposed. The experimental results show 5-m spatial resolution and up to 6.3-MHz frequency response with 50-ns pulse width are achieved in 1150-m sensing distance. Another system based on Polarization-OTDR (P-OTDR) [9] has achieved 10-m spatial resolution in 1-km sensing range, while the detected frequency response is 5 KHz. But this P-OTDR system can only locate beginning point of the vibration events because the backscattered signals after the first disturbing point are contaminated by their previous perturbations.

However, all of the above optical fiber distributed vibration sensors cannot locate the lateral position of vibration source. They can only locate the position along the sensing fiber. In most applications like pipeline intrusion security monitoring and power cable intrusion security monitoring, lateral locating is required. That means we need to determine the vertical distance between vibration source and sensing fiber. By this way, we can make sure of the degree of danger of intrusion.

In this manuscript, we present a novel lateral locating method for optical fiber distributed vibration sensing system based on

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phase-sensitive OTDR. Two points of the sensing fiber are selected as the vibration sensor. By measuring the time difference of vibration signals reaching two sensors, we can calculate the vertical distance between intrusion and sensing fiber. We have carried out the test for six times. Our test results show that the locating accuracy is about 2.10 m with 100-MHz sampling rate, 1-kHz pulse repetition rate, and 1500 sampling points within one pulse interval.

2. Lateral locating method

The lateral locating method for optical fiber distributed vibration sensing system depends on time difference of arrival. The model of lateral locating method is shown in Fig. 1.

We choose two points as vibration receiving sensors from the sensing fiber. $S_1(x_1, y_1, z_1)$ is the first receiving sensor, and $S_2(x_1, y_1, z_2)$ is the second receiving sensor. $S(x, y, z)$ is the position of vibration source, and the line of S–S_1 is perpendicular to the sensing fiber line, d is the distance between S_1 and S_2, t_1 is the travel time from S to S_1, t_2 is the travel time from S to S_2, and Δt is the time difference between t_1 and t_2.

$$(\upsilon t_1)^2 + d^2 = (\upsilon t_2)^2 \quad (1)$$

where υ is the propagation speed of vibration, $t_2 = t_1 + \Delta t$. Replace t_2 with t_1, therefore,

$$d^2 = (\upsilon \Delta t)^2 + 2\Delta t t_1 \upsilon^2 \quad (2)$$

From Fig. 1 we can know that $y = \upsilon t_1$, replace υt_1 with y_{s-s_1}, therefore,

$$y_{s-s_1} = \frac{d^2 - (\upsilon \Delta t)^2}{2\upsilon \Delta t} \quad (3)$$

$$y = \sqrt{{y_{s-s_1}}^2 - D^2} \quad (4)$$

where y_{s-s_1} is the distance between S and S_1, y is the parallel distance between S and S_1, D is the depth of the sensing fiber buried under the ground, Δt is the time difference between t_1 *and* t_2, which is measured by sensors S_1 and S_2, as shown in Fig. 2.

3. System configuration and signal processing

3.1. System configuration

The schematic diagram of optical fiber distributed intrusion sensing system is shown in Fig. 3.

A laser with ultra-narrow linewidth of less than 5 kHz is used as the light source, which generates CW light with center wavelength of 1550.2 nm and low frequency drift. The maximum output optical power of the laser is ~10 mW. The light is then modulated into sequence of pulses with repetition rate of 1 kHz induced by an acoustic-optic-modulator (AOM), where AOM is modulated by an arbitrary function generator (AFG). The narrow pulse width is set to be 30 ns for 3-m spatial resolution. After that, the narrow pulses is amplified to 1 W by an Erbium-doped Fiber

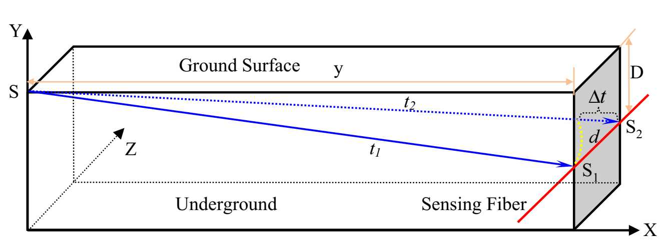

Fig. 1. The model of lateral locating method.

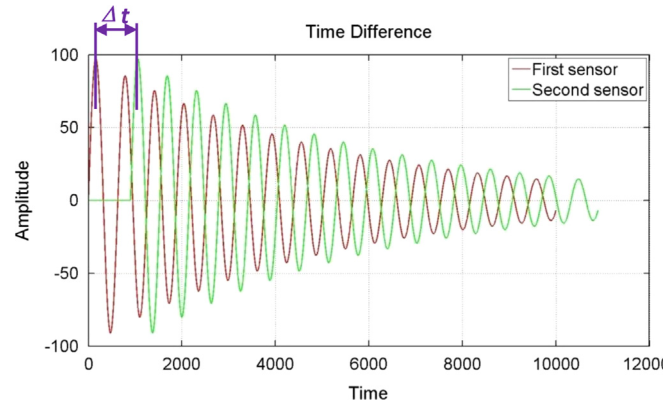

Fig. 2. Time difference between t_1 and t_2.

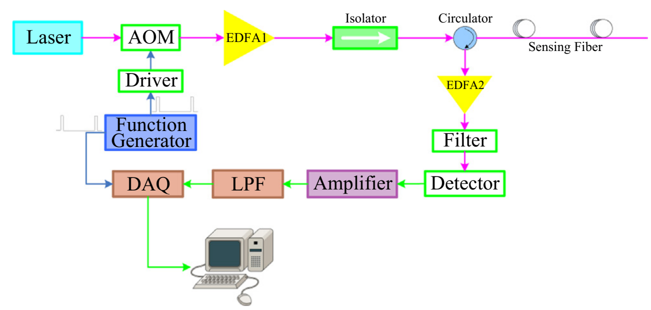

Fig. 3. Schematic diagram of optical fiber distributed intrusion sensing system.

Amplifier (EDFA1) and injected into the sensing fiber (Corning SM-28e+) to generate Rayleigh backscattering light, which is then collected by a circulator. The backscattering light is amplified by EDFA2, and then filtered by a FBG filter to remove spontaneous emission. Then the Rayleigh backscattering signal is amplified by an amplifier after detected by the InGaAs detector of 100-MHz bandwidth. Thereupon, the Rayleigh backscattering signals passes through a low-pass-filter (LPF) with the pass band width from 2 Hz to 1 kHz, and finally it is sampled by an acquisition card with 100-MHz sampling rate and 1500 sampling points per interval.

3.2. Signal processing

To achieve a fully distributed vibration sensing system with the function of lateral locating, the signals collected by DAQ card (ADLINK-PCIe-9842) have been processed in this system. First, one Rayleigh backscattering curve is stored onto the on-board memory of the DAQ card every 1 ms, corresponding to a 1-kHz pulse repetition rate. Once the memory is filled up, all of curves will be transferred to computer to be further analyzed. The signal processing method is shown in Fig. 4.

In this system, we process the data by the Matlab software. The data of each position, collected by a data acquisition card, will be rearranged according to the time to be vibration signals. First, the signals at a certain position will be extracted out by the moving differential method [11]. Second, the point that has largest vibration amplitude in all vibration curves as the first sensor needs to be searched out. The point on the sensing fiber, which has the largest vibration amplitude, is the nearest from the vibration source (S_1). Third, the point that is 5 m away from S_1 should be taken out as the second sensor (S_2). And then, calculate the time difference between S_1 and S_2. In order to get a higher locating accuracy, we need to calibrate the propagation speed of vibration in soil before first calculating the lateral position of vibration