

Distributed optical fiber perturbation sensing system based on Mach-Zehnder interferometer

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Abstract A novel distributed optical fiber vibration-sensing system based on Mach-Zehnder interferometer has been designed and experimentally demonstrated. Firstly, the principle of Mach-Zehnder optical path interferometer technique is clarified. The output of the Mach-Zehnder interferometer is proportional to the phase shift induced by the perturbation. Secondly, the system consists of the laser diode (LD) as the light source, fiber, Mach-Zehnder optical interferometers as the sensing units, a $1 \times N$ star fiber-optic coupler, an $N \times 1$ fiber-optic coupler, a photodiode (PD) detector, and a computer used in signal processing. The entire monitoring region of this system is divided into several small zones, and each small monitoring zone is independent from each other. All of the small monitoring zones have their own sensing unit, which is defined by Mach-Zehnder optical interferometer. A series of sensing units are connected by the star fiber-optic couplers to form a whole sensing net. Thirdly, signal-processing techniques are subsequently used to calculate the phase shift to estimate whether intruders appear. The sensing system is able to locate the vibration signal simultaneously, including multiple vibrations at different positions, by employing the time-division multiplexed (TDM) technique. Finally, the operation performance of the proposed system is tested in the experiment lab with the conditions as follows: the number of the sensing units is 3, the length of the sensing fiber is 50 m, and the wavelength of the light diode is 1550 nm. Based on these investigations, the fiber surrounding alert system is achieved. We have experimentally demonstrated that the sensing system can measure both the frequency and position of the vibration in real time, with a spatial positional resolution better than 50 m in an area of 1 km².

Keywords distributed, Mach-Zehnder interferometer, time-division multiplexed (TDM), vibration

1 Introduction

With the development of optical communication technology, optical sensing technology has also been rapidly developing [1]. Recently, research and application of distributed optical fiber sensing system have attracted extensive attention. Fiber-optic sensors are emerging as sensors of choice in many applications. In sensing and measurement of strain and vibration, optical fiber sensors provide advantages over the existing technologies. Because of their small size and geometric adaptability, optical fibers can be easily embedded within concrete structures and installed under the soil. Most importantly, at the same time, they serve the dual purpose of being the sensor as well as the pathway for the sensor signals out of the structure. There are two methods being used in sensor vibration sensor signals. Localized fiber-optic sensors set out the strain and vibration with a specific segment of the optical fiber and are thus similar to conventional vibration gauges. Distributed sensors make full use of optical fibers in which each element of the optical fiber is used for both sensing and data transmission. Distributed sensors are most appropriate for structural applications because of their multipoint measurement capabilities [2].

Distributed optical fiber vibration-sensing system detect and locate nonconcurrent external signals along the whole length of the fiber, applications range from fire detection to strain sensing in intrusion detection systems. The most distinguished techniques for distributed sensing involve the use of the optical time domain reflectometer (OTDR) and the optical frequency domain reflectometer (OFDR) [3,4]. They sense signals by measuring the optical characteristics of various reflective light waves coming from spatially distributed backscattering such as Rayleigh, Brillouin, or Raman. However, there are some limitations on these traditional methods. For example, the scattering light is usually so weak that the performance requirement of detection techniques is high, but the sensitivity is low. Also, the injected pulsed light is not suitable for detecting

time-varying signals. In these cases, more economic and effective methods are in great demand in the distributed sensing area. There has been considerable interest recently in the development of fiber-optic sensors based on interferometry. The use of such a technique for distributed strain or temperature sensing in advanced composite or other structural materials has been discussed in several recent articles. Because of the extremely high sensitivity for phase modulation, fiber-optic interferometer sensors have shown several distinct advantages in measuring vibrations. Mach-Zehnder optical path interferometer technique, which is the most simple, practical, and accurate technique, is used in the vibration-sensing system. The main advantages of this technique lie in its ability to facilitate absolute measurements, such as position and displacement, with high resolution.

In this paper, we design and demonstrate a novel distributed optical fiber vibration-sensing system based on Mach-Zehnder interferometer. Each Mach-Zehnder interferometer is a sensing unit, and the units work independently without affecting others. Several sensing units use a $1 \times N$ star fiber-optic coupler to make up a system, which detects and locates intruders in a certain area. Perturbations such as strain or vibration variations on the fiber interferometer yield an output proportional to the product of the rate of phase change. The output of the Mach-Zehnder interferometer is proportional to the phase shift induced by the perturbation and contains no spatial information. The ratio of these two output signals results in information on the position of the disturbance. Signal-processing techniques are subsequently used to calculate the rate of phase shift to estimate whether there are intruders. The sensing system is able to locate and recover the vibration signal simultaneously, including multiple vibrations at different positions. The operation performance of the proposed device is theoretically analyzed and experimentally demonstrated [5,6].

2 Configuration of sensing system

The configuration of this distributed optical fiber vibration-sensing system is shown in Fig. 1.

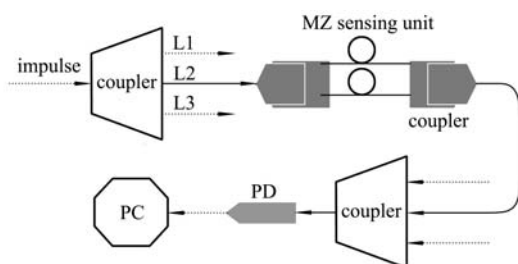


Fig. 1 Configuration of distributed optical fiber vibration-sensing system

As Fig. 1 shows, the system consists of the laser diode (LD), fiber-optic Mach-Zehnder optical interferometer, a $1 \times N$ star fiber-optic coupler, an $N \times 1$ fiber-optic coupler, a photodiode (PD) detector, and computer processing system. The system divides the entire monitoring region into several small zones, and each small monitoring zone is independent. All of the small monitoring zones have their own sensing unit, which is made by Mach-Zehnder optical interferometer — a series of sensing units connected to one another to form a whole sensing net. Light from a source is divided into several equal parts by a $1 \times N$ star fiber-optic coupler launched into each unit's sensing fiber separately [7]. In each sensing unit, the light is divided at the second time into two equal parts by a 1×2 optic coupler, one launched into the Mach-Zehnder reference arm and the other into the sensing arm. All the outputs of the Mach-Zehnder interferometers are clustered by the $N \times 1$ optic coupler. The optical signals are transformed to electric signals. Because of using the time-division multiplexed (TDM) technology, the output signals are followed on the timeline. Just as unit 1's output is arrayed in the first period of time tagged T1, unit 2's output is arrayed in the second period of time tagged T2, and so on. After all signals are detected and sent to the signal-processing system, they will arrange on the timeline in accordance with each sensing unit. Therefore, just by analyzing each period's signal of the time domain, we will be able to determine the vibration of the corresponding sensing unit. The output of the Mach-Zehnder interferometer is proportional to the phase shift induced by the perturbation and contains no spatial information. Signal-processing techniques are subsequently used to calculate the rate of phase shift. The ratio of these output signals results in information on the position of the disturbance. The sensing unit does not have the function of locating, a unit that only estimates the perturbation and judges whether the zone it monitors has an intruder. However, all the units connect to a monitoring net, with the entire monitoring system; the intruding information can be detected and located.

3 Theory

As a continuous distributed sensing method, spatial resolution and strain measurement accuracy are the main concerns of the Mach-Zehnder optical path interferometer technique. For the interferometric distributed optical fiber sensor, the principle of theory is the phase modulation. Sensing fiber will be placed under the testing conditions; when the fiber is subject to vibration from the external environment, the fiber's optical length, diameter, and refractive index are changing with the vibration. Then, these changes eventually lead to optical phase change. Therefore, measurement of the light phase change can estimate the corresponding rate of the vibration.

Light wave transit through a fiber with its length denoted as l and the phase delay as $\phi = \beta l$, where β is the spread constant. When the sensing fiber is subject to vibration from the external environment, the parameters of the fiber will change. Longitudinal strain effect causing the change in fiber length is denoted as Δl ; Poisson horizontal effect leads to change in the diameter of fiber core denoted as Δa , which, moreover, bring on the change of the spread constant denoted as $\Delta \beta$. With the above-mentioned information, the change of these parameters eventually leads to optical phase diversification:

$$\Delta \phi = \Delta(\beta l) = \beta l \left(\frac{\Delta l}{l} \right) + l \left(\frac{\partial \beta}{\partial n} \right) \Delta n + l \left(\frac{\partial \beta}{\partial a} \right) \Delta a,$$

where $\beta l(\Delta l/l)$ is the phase difference caused by the change of the sensing fiber, $l(\partial \beta / \partial n) \Delta n$ is the phase difference caused by the change of the refractive index of the fiber, and $l(\partial \beta / \partial a) \Delta a$ is the phase difference caused by Poisson effect and always negligible because the value is small [8].

From the elastic strain theory, the phase difference of the light wave can be expressed as

$$\frac{\phi_s + \phi_\varepsilon}{pL} = nk_0 \frac{2u}{E} + \frac{k_0}{2E} n^3 [(1-u)P_{11} + (1-3u)P_{12}],$$

where L is the length of the arm, p is the pressure on the fiber, P_{11} and P_{12} are the parameters of the change of the fiber caused by the pressure, u and k_0 are the index of the phase-change. Phase change is proportional to the length of the fiber and the stress on the sensing fiber. By analyzing the range of the vibration, the system will be able to monitor the external environment [9].

The system is based on the Mach-Zehnder interferometer; the configuration of this interferometer in optical fiber vibration-sensing system is shown in Fig. 2.

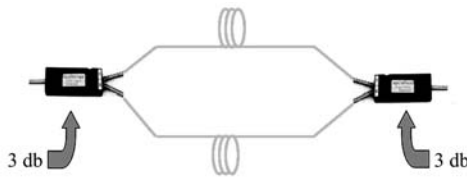


Fig. 2 Configuration of Mach-Zehnder interferometer

The laser is divided into two equal parts by a 1×2 optic coupler, one launched into the Mach-Zehnder reference arm and the other into the sensing arm; when there are vibrations put on the fibers, the fiber's optical geometric parameters, such as size and refractive index, are changed, and therefore, the phase difference between reference light and signal light will alter. The phase difference of the output light wave can be expressed as

$$\Delta \phi = \Delta \phi_s + \Delta \phi_\varepsilon + \Delta \phi_0 + \Delta \phi_n,$$

where $\Delta \phi_s + \Delta \phi_\varepsilon$ is the phase difference caused by the vibrations and press, $\Delta \phi_0$ is dependent on the length difference between the reference arm and signal arm, and $\Delta \phi_n$ is caused by the phase noise. The output light intensity is

$$I = \frac{1}{2} I_0 + \frac{1}{2} I_0 \cos(\Delta \phi_s + \Delta \phi_\varepsilon + \Delta \phi_0 + \Delta \phi_n).$$

When the differences of the output light intensity are detected, the system could be able to monitor the vibrations by analyzing the range of the light intensity.

4 Results and discussion

The shape of the light pulse from the LD is shown in Fig. 3, where V denotes the voltage.

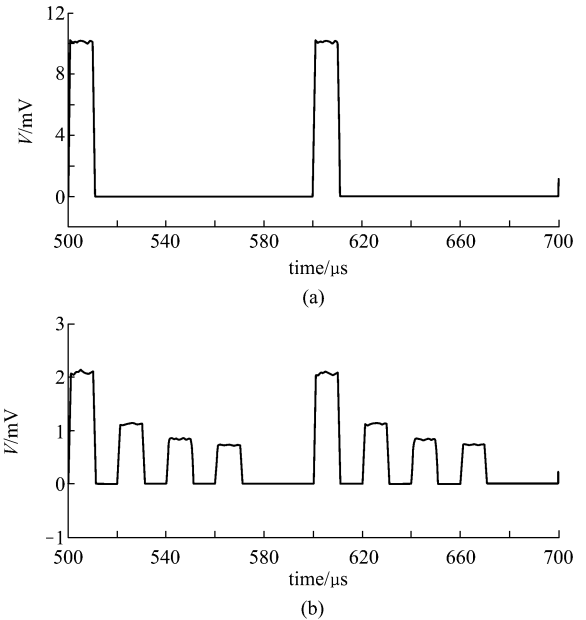


Fig. 3 Laser pulse from LD. (a) Marker laser pulse; (b) all laser pulse

The data on no vibration are as follows: when the frequencies are 0–1000 Hz, 1000–3000 Hz, 3000–5000 Hz, 5000–7000 Hz, 7000–9000 Hz, and > 9000 Hz, $n = 908, 2, 32, 0, 0$, and 4, respectively.

The data on vibration are as follows: when the frequencies are 0–1000 Hz, 1000–3000 Hz, 3000–5000 Hz, 5000–7000 Hz, 7000–9000 Hz, and > 9000 Hz, $n = 403, 170, 78, 61, 43$, and 196, respectively.

The data are shown in Figs. 4 and 5, where f denotes the frequency.

Therefore, the system could distinguish whether there are vibrations on the fibers by analyzing the V - f data.

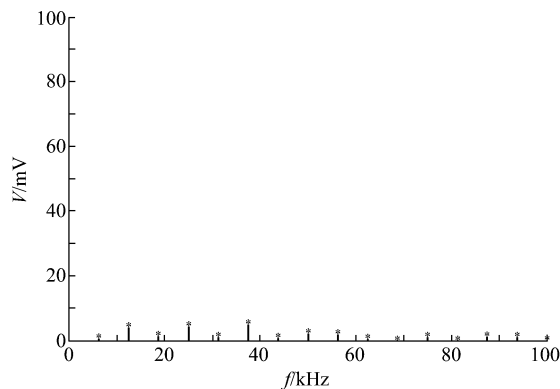


Fig. 4 V - f curve on no vibration case

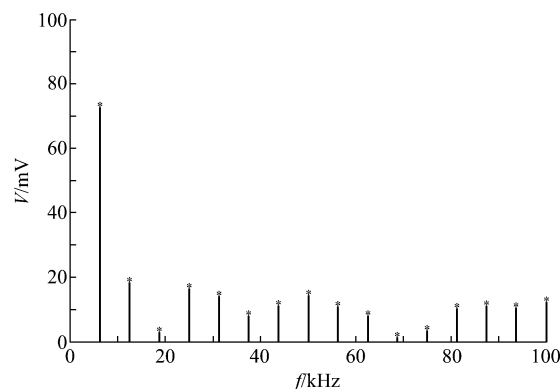


Fig. 5 V - f curve on vibration case

5 Conclusion

The paper presented a novel distributed fiber-optic vibration sensor, employing simple Mach-Zehnder optical interferometer. We have experimentally demonstrated

that the sensor can measure both the frequency and position in real time, with a spatial positional resolution better than 50 m.

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