A Distributed Acoustic Sensing System for Vibration Detection and Classification in Railways

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Abstract: A distributed acoustic sensing (DAS) system is proposed and a data processing method for vibration is designed in this paper. The proposed DAS system is based on the Rayleigh scattering signal and utilizes phase-sensitive optical time-domain reflectometry (ϕ-OTDR) to demodulate the environmental vibration. It can collect the vibration information in railways and implement vibration classification based on the feature of sensed vibration signals. This system has been deployed in Guangzhou Shenzhen High-Speed Railway, and the experimental results validate its effectiveness.

Keywords: DAS; φ-OTDR; vibration classification

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1 Introduction

Optical fibers are the carrier of optical signals for optical fiber communications, which have been research hotspots since its introduction. Recently, with the development of relevant research, optical fiber sensing technology has drawn more and more attention. Fiber can work as the sensing component and sense environmental variations, such as vibration, temperature, and strains[1]. Several researchers have applied optical fiber sensing to geophysics and obtained several achievements[2–4].

In addition to seismic wave monitoring in geophysics, distributed optical fiber sensing (DOFS) is a widely applied classical fiber sensing technology[5]. While an optical signal transmits through the fiber, the backscattering signals are generated and also propagated along the optical fiber. The scattering signals generated in different positions arrive at the start of fiber at different time points. Besides, the parameters of backscattering signals are related to environmental parameters in the scattering position. Hence, the sensing information can be obtained by analyzing the backscattering signals. These are the basic principles of DOFS.

Distributed acoustic sensing (DAS) is one Rayleigh scattering DOFS technology[6]. By applying a narrowband laser, coherent detectors can detect optical Rayleigh backscatter signals and obtain electrical signals. The electrical signal is sampled by an analog-to-digital converter (ADC) and further used to sense acoustic information by digital signal processing (DSP). Due to its high sensitivity, DAS is widely applied to provide unmanned real-time leak monitoring in the oil and gas industry.

Traffic monitoring is another important use case for DAS[7]. Traffic information can be obtained by analyzing sensing vibration information provided by DAS system. The characteristics of low cost and high coverage also match long-distance railways. However, the requirement of railway monitoring focuses on the identification of vehicle positions and intrusion detection, which involves positioning and vibration differentiation. To achieve this requirement, we propose a DAS system for railways in this paper, which can detect and locate vibration of vehicles and recognize the intrusion behavior.

This innovative solution can identify railway surrounding events through DAS systems utilizing single mode optical fibers within the communication network. This approach not only enhances the capabilities of communication infrastructure but also expands its potential commercial value. This system has been deployed in Guangzhou Shenzhen High-Speed Railway and the experimental results verified its effectiveness.

The remainder of this paper is organized as follows. Section 2 introduces the theory and principle of the DAS system. The proposed DAS system is designed and the data processing steps are given in Section 3. Experimental setup and results are given in Section 4 and we conclude this paper in Section 5.

2 Theory and Principle

The DAS system based on phase-sensitive optical time-domain reflectometry (ϕ-OTDR)[7] is introduced in this section, where the probe pulse signal is injected into the fiber and the sensing information is derived by analyzing the scatting signal. The probe pulse signal can be described as:

$$S_t = A_t \exp\left[i\left(\omega_t + \phi_t\right)\right], \tag{1}$$

where A_t, ω_t and ϕ_t are the amplitude, angular frequency, and phase of probe pulse signal i is the imaginary unit.

The probe pulse transmits through the fiber and generates the Rayleigh scattering signals. Rayleigh scattering does not change the frequency of light[8], and the scattering signal can be described as:

$$S_s = A_s \exp\left[i\left(\omega_t + \phi_s\right)\right], \tag{2}$$

where A_s, ω_t and ϕ_s are the amplitude, angular frequency, and phase of the Rayleigh scattering signal. The amplitude and phase are related to the strain received by the fiber. Therefore, the vibration information can be sensed.

To demodulate the parameters of the scattering signal, the coherent detection technology is applied. In a coherent detector, the local-oscillator (LO) signal and scattering signal work as inputs together and they should be at the near frequencies. Considering the heterodyne reception technology, the LO signal can be described as:

$$S_O = A_O \exp\left[i\left(\omega_O + \phi_O\right)\right], \tag{3}$$

where A_O, ω_O and ϕ_O are the amplitude, angular frequency, and phase of the LO signal. $\omega_{\mathrm{IF}} = \omega_O - \omega_t \neq 0$ is the frequency difference between the LO signal and scattering signal and represents the frequency of intermediate frequency signals.

The LO signal and scattering signal interfere and output two intermediate frequency signals after the hybrid. Two photodetectors convert the light signals into electrical signals, which can be described as:

$$\begin{cases} S_I = \frac{1}{2} R\left[A_s A_O \cos\left(\omega_{\mathrm{IF}} t + \phi_s - \phi_O\right) + A_s^2 + A_o^2\right] \\ S_Q = \frac{1}{2} R\left[A_s A_O \sin\left(\omega_{\mathrm{IF}} t + \phi_s - \phi_O\right) + A_s^2 + A_o^2\right]. \end{cases} \tag{4}$$

These medium-frequency electrical signals are down-converted into baseband signals by digital signal processing, and the DC components are filtered. The AC electrical signals are obtained as

$$\begin{cases} I_I = \frac{1}{2} R A_s A_O \cos\left(\phi_s - \phi_O\right) \\ I_Q = \frac{1}{2} R A_s A_O \sin\left(\phi_s - \phi_O\right), \end{cases} \tag{5}$$

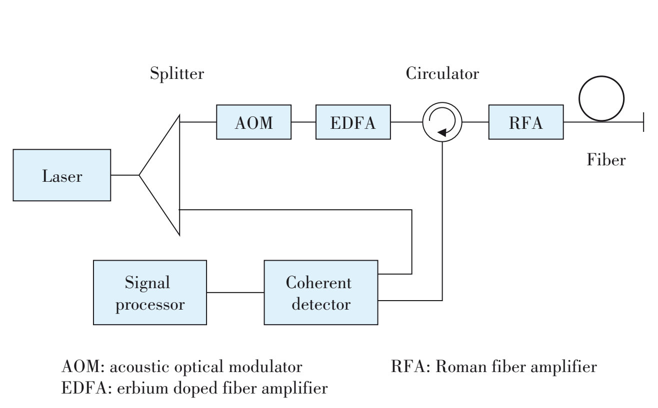
where R is the response factor of the photodetector.

There amplitude A_s and phase ϕ_s can be demodulated as follows:

$$\begin{cases} A_s \propto \sqrt{I_I^2 + I_Q^2} \\ \phi_s \approx \arctan \frac{I_Q}{I_I} + \phi_O . \end{cases} \tag{6}$$

3 System and Data Process

In this paper, we propose a DAS system as shown in Fig. 1. The laser generates a light signal, and one acoustic optical modulator (AOM) is utilized to modulate the probe pulse with a certain frequency shift. The AOM can achieve a high extinction ratio (ER) to support the following accurate date process. To achieve enough sensing length, the probe pulse is amplified by an erbium doped fiber amplifier (EDFA) before being injected into the fiber. Then the amplified probe pulse transmits through the fiber and generates backscatter signals. The Roman fiber amplifier (RFA) is utilized to keep probe pulse power sufficient during transmission. The scattering signals generated in different positions arrive at the

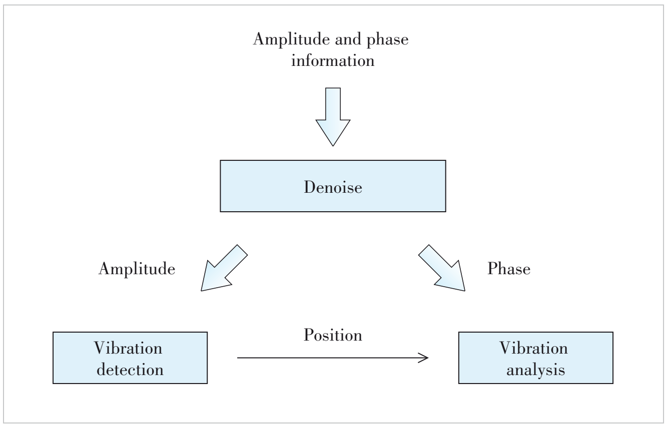


▲**Figure 1. Proposed distributed acoustic sensing (DAS) system** circulator at different times, and they can be distinguished in the time domain. For a specific scattering signal, it passes the circulator. The LO signal enters the coherent signal with the scattering signal, where the LO signal is one part light from the laser. As introduced in Section 2, the amplitude and phase of the scattering signal can be demodulated, which can be described as $A_{i,j}$ and $\phi_{i,j}$, where i represents this scattering signal is generated by the i-th probe pulse in the j-th position.

In the data processor, the vibration of vehicle detection and intrusion behavior recognition are realized based on the amplitude and phase information, and the detailed process is shown in Fig. 2. First, the denoising step is needed to achieve high accuracy. Then, the amplitude information is used to detect the vibration. The amplitudes generated by the i-th probe pulse are represented as the sequence $\left[A_{i,1}, A_{i,2},\cdots, A_{i,m}\right]$, where m is the toal number of scattering signal sampled by ADC. The amplitude difference sequence $\left[\Delta A_{i,1}, \Delta A_{i,2},\cdots, \Delta A_{i,m-1}\right]$ is calculated by $\Delta A_{i,k} = \left|A_{i,k+1} - A_{i,k}\right|$, where $k = 1, 2,\cdots, m - 1$. The peak value $\Delta A_{i,j}$ represents that the vibration occurs at the j-th position.

The short-term energy and short-term zero-crossing rate are used to detect the vibration position based on the amplitude sequence. Furthermore, the vibration may be caused by different reasons, and they can be classified into different vibration types. Supposing the vibration is detected at the j-th position in the i-th probe pulse, the phases at different times can be represented as sequence $[\phi_{i,j}, \phi_{i+1,j},\cdots, \phi_{i+n,j}]$, where n is the total number of record phases. $[\Delta\phi_{i,j}, \Delta\phi_{i+1,j},\cdots, \Delta\phi_{i+n-1,j}]$ is the phase difference sequence, which corresponds to the vibration waveform modulation on the scattering signal, where $\Delta\phi_{i,j} = \phi_{i+1,j} - \phi_{i,j}$.

The time-frequency signal is obtained through a short-time Fourier transform of the phase difference sequence, and the features of the time-frequency signal are used in the following vibration classification. In detail, the key step of identifying vibration events is to select appropriate audio features to characterize the corresponding vibration waveform. In our system, we adopt the spectral image feature (SIF) of the phase difference sequence, which involves a short-time Fourier transform on the original sequence and the preprocessing of the two-dimensional time-frequency features.



▲**Figure 2. Proposed data processor**

▲**Figure 3. Fiber laying scenario**

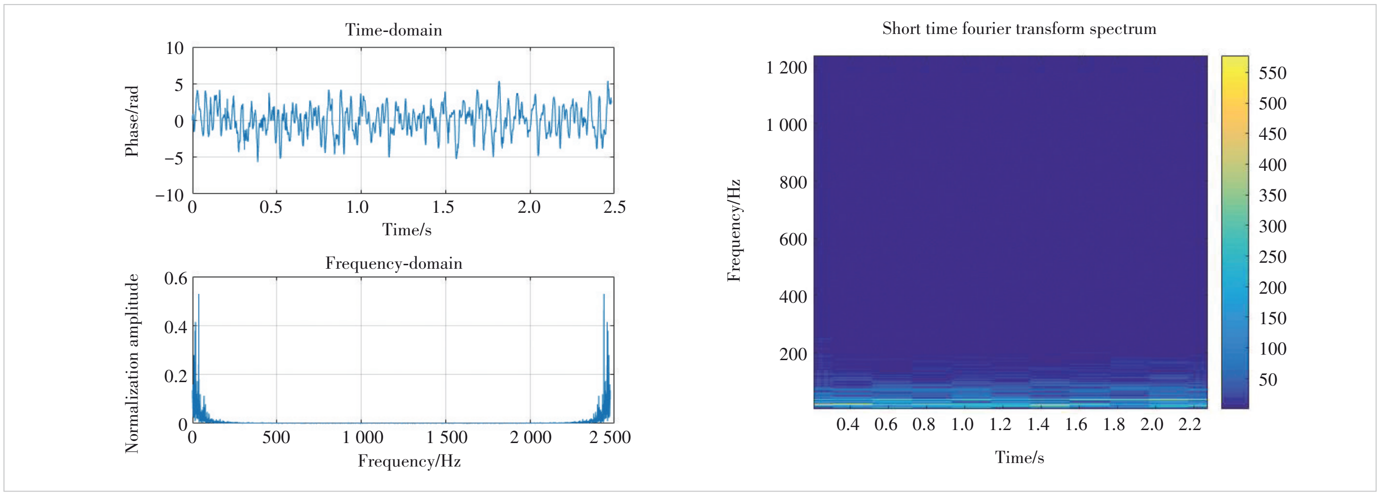
4 Experimental Setup and Results

The proposed DAS system has been deployed in the Guangzhou Shenzhen High-Speed Railway. The sensing fiber is approximately 20 km long and is laid on railways through fixing with guardrails (Fig. 3). Through extensive testing and comparison of optical fiber deployment methods, it was found that the S-shaped optical fiber deployment has advantages in terms of the accuracy of vibration signal acquisition and accuracy of system identification for different events.

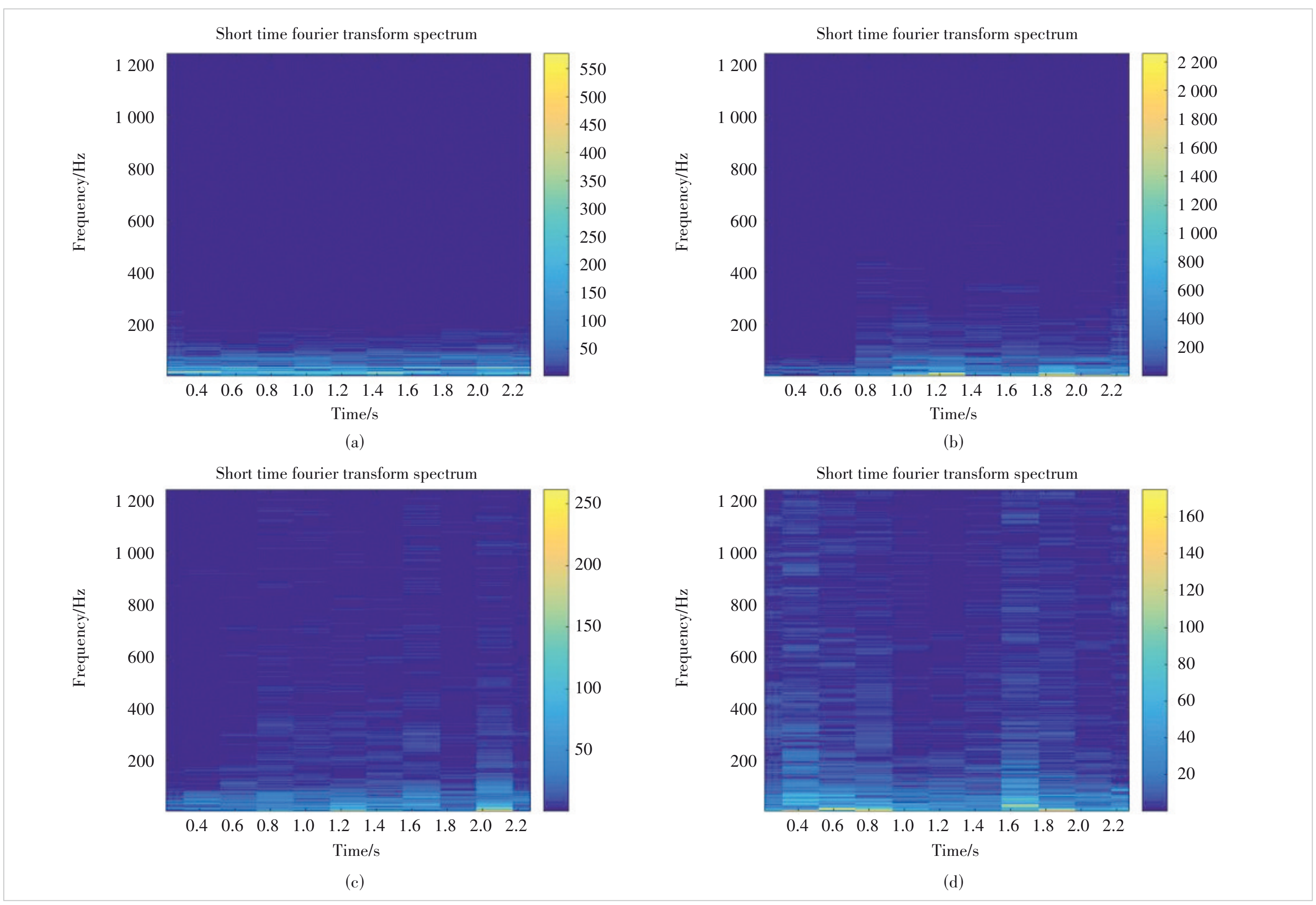
The laser generates the pulse light signal with a power of 23 dBm at 1 550.12 nm. The split ratio is set as 1:1. The repetition time of the probe pulse is set as 0.4 ms, which can cover the round-trip time of the probe pulse in a 40-km fiber. The width of the probe pulse is 80 ns, which corresponds to the spatial resolution of 8 m. The frequency shift introduced by AOM is 80 MHz. In RFA, the wavelength of pump light is 1 450 nm and the power is set as 21 dBm. The system can support the max sensing length of 40 km under these setups.

Fig. 4 shows a specific vibration signal. On the left, the time-domain signal and the frequency-domain signal are given, respectively. The time domain signal is the phase difference sequence obtained from the above step, which shows the vibration waveform. The time-domain signal has several features and the frequency-domain signal is obtained by the Fourier transform. It can be observed that the frequency-domain signal is between 0 to 2 500 Hz, and it mainly contains the low-frequency part (lower than 500 Hz) and high-frequency part (higher than 2 000 Hz). The time-frequency spectrum signal shown on the right is obtained by the short-time Fourier transform, and the colors correspond to different frequencies.

Fig. 5 gives several time-frequency spectrum signals of different situations, where Fig. 5(a) corresponds to the situation where there are no vehicles or intrusions, Fig. 5(b) the situation where there is a vehicle but no intrusion, Fig. 5(c) the situation where there are intrusions but no vehicle, and Fig. 5(d) the situation where there are both vehicles and intrusions. It can be seen that the proportion of high-frequency components varies. Based on this, we can design a classification algorithm to recognize different vibration situations. In our ex-



▲Figure 4. Vibration signal



▲Figure 5. Time-frequency spectrum signals in different situations periment, the classification accuracy can achieve 90%.

5 Conclusions

In this paper, we propose one DAS system to realize vibration detection and classification for railways. This system is based on φ-OTDR, and the amplitude and phase demodulated from scattering signals are analyzed to obtain the vibration waveform. Further, the vibration waveform is converted to the time-frequency spectrum signals, which show the frequency feature and are used for vibration situation classification. This system has been deployed in Guangzhou Shenzhen High-Speed Railway, and the classification accuracy can achieve 90%.

References

[1] LEE B. Review of the present status of optical fiber sensors [J]. Optical fiber technology, 2003, 9(2): 57 – 79. DOI: 10.1016/s1068-5200(02)00527-8

[2] MARRA G, CLIVATI C, LUCKETT R, et al. Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables [J]. Science, 2018, 361(6401): 486 – 490. DOI: 10.1126/science.aat4458

[3] MARRA G, FAIRWEATHER D M, KAMALOV V, et al. Optical interferometry-based array of seafloor environmental sensors using a transoceanic submarine cable [J]. Science, 2022, 376(6595): 874 – 879. DOI: 10.1126/science.abo1939

[4] ZHAN Z W, CANTONO M, KAMALOV V, et al. Optical polarization-based seismic and water wave sensing on transoceanic cables [J]. Science, 2021, 371(6532): 931 – 936. DOI: 10.1126/science.abe6648

[5] LU P, LALAM N, BADAR M, et al. Distributed optical fiber sensing: review and perspective [J]. Applied physics reviews, 2019, 6(4): 041302. DOI: 10.1063/1.5113955

[6] SHANG Y, SUN M C, WANG C, et al. Research progress in distributed acoustic sensing techniques [J]. Sensors, 2022, 22(16): 6060. DOI: 10.3390/s22166060

[7] LIU H Y, MA J H, XU T W, et al. Vehicle detection and classification using distributed fiber optic acoustic sensing [J]. IEEE transactions on vehicular technology, 2020, 69(2): 1363 – 1374. DOI: 10.1109/TVT.2019.2962334

[8] WANG Z N, ZHANG L, WANG S, et al. Coherent Φ-OTDR based on I/Q demodulation and homodyne detection [J]. Optics express, 2016, 24(2): 853 – 858. DOI: 10.1364/oe.24.000853

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