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Multiband imaging and characteristic spectrum extraction of optical fiber intrusion signal

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ABSTRACT

This paper proposes a multiband imaging method for optical fiber intrusion signals to realize the multi-dimensional analysis and the characteristic spectrum extraction. Firstly, the time-frequency analysis technique is performed on the initial collected intrusion signals to obtain the time-frequency distribution at each spatial intrusion position, on which energy band-wise integration is carried out along the frequency direction to generate spatial-temporal two-dimensional images in each frequency band. Then, these images are further stacked up as layers resulting in a spatial-temporal-frequency three-dimensional (3-D) cubic data. Based on this data, we extract the characteristic spectrums as the features of the intrusion signals. The real data experiments verify the effectiveness of this method.

1. Introduction

Optical fiber intrusion signal processing method is an important foundation for the OFPS to realize the continuous full-path measurement as well as the real-time monitoring [1]. Conventional methods for analyzing the optical fiber intrusion signal are usually studied from a mathematical point of view on the one-dimensional signals that may carry intrusion information in time [2], frequency [3,4] or time-frequency [5–7] domain. From a single dimension perspective, it is easy to lose the possible higher dimensional information, and more importantly, lack of exploration of the physical interpretation involved in the intrusion signal itself. The OFPS exploit the laying of the underground cable to detect and identify the external intrusion signals so that it can compute the place and time of the occurrence of any abnormal event [8]. The soil medium act as a carrier of vibration information to propagate the intrusion signals that act further on the underground cable, which modulates the optical signal transmitted in the fiber and ultimately causes the optical signal to carry the intrusion information [9,10].

The intrusion signals generated by different forms of vibration have different spectral distributions indeed. In addition, the effect on the soil medium is actually different for various intrusion signals, so that the specific spectrum of the intrusion signal received by the OFPS is determined by the specific form of the intrusion signal as well as the physical position of the intrusion source. In order to analyze the form of intrusion signal accurately under the physical location of specific intrusion source, we propose a method to extract the characteristic spectrum of the intrusion signal, which express the energy distribution of the intrusion signal in different frequency bands. In this paper, the time-frequency analysis is used to add the frequency dimensional information on the basis of spatial-temporal two-dimensional image representation of optical fiber intrusion signal. And the time-frequency analysis performed on the optical fiber intrusion signal is a more comprehensive method increasing the observed dimensions. Furthermore, the spatial-temporal-frequency 3-D imaging results are formed, which can be seen as a joint expression of the spatial-temporal distribution and the frequency characteristic of the fiber intrusion signal presented in the form of data cube stacked in frequency band sequence. On this basis, we can further extract the characteristic spectrums corresponding to each intrusion time and spatial position as the features of the optical fiber intrusion signals. This method may open up a new direction for further research on the feature extraction and type recognition of intrusion signals from a physical point of view.

2. Multiband imaging and characteristic spectrum extraction of optical fiber intrusion signal

Fig. 1 shows the sketch of multiband imaging and characteristic spectrum extraction method of the optical fiber intrusion signal. The OFPS exploit the laying of the underground cable to analyze the intrusion signal, which is a two-dimensional time-spatial distribution of the optical fiber intrusion signal representing accurately the actual physical location of the intrusion occurrence as well as corresponding time. However, conventional methods for representing the optical fiber

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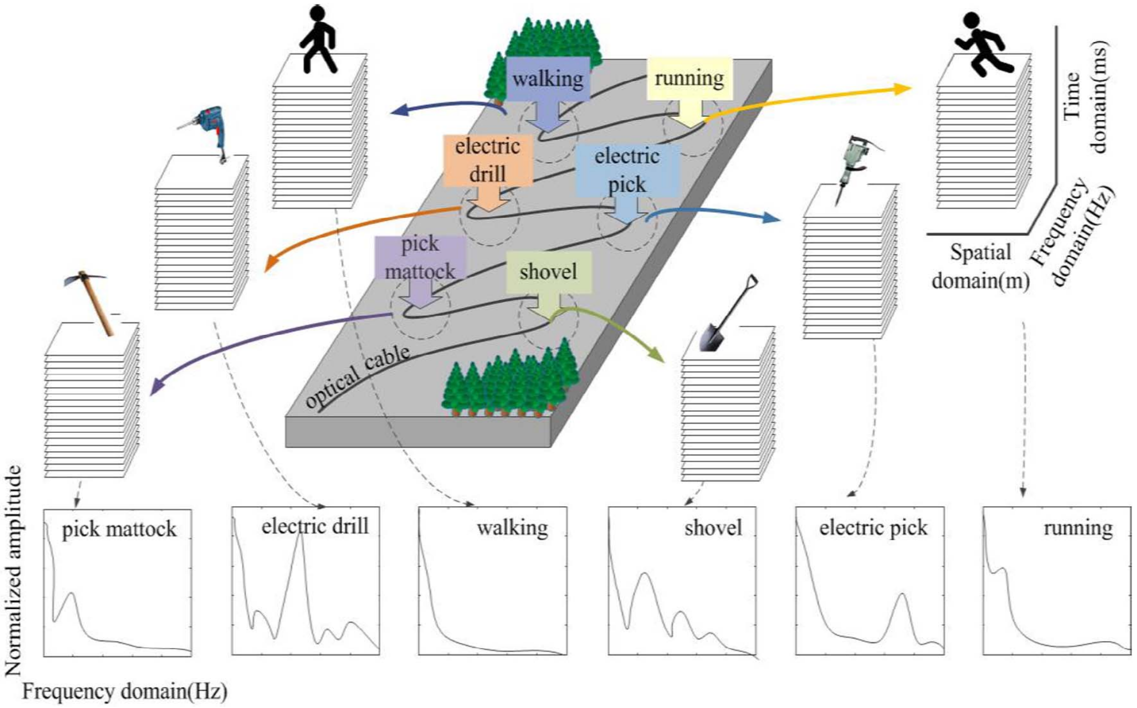

Fig. 1. Sketch of multiband imaging and characteristic spectrum extraction of the optical fiber intrusion signal.

intrusion signal lack the observing ability for the frequency dimension, so we attempt a spatial-temporal-frequency 3-D representation of the optical fiber intrusion signal. Firstly, the time-frequency analysis is performed on the optical fiber intrusion signal to obtain the time-frequency distribution at each spatial position, on which energy band-wise integration is carried out along the frequency direction to generate the spatial-temporal two-dimensional images in each frequency band. Then, these two-dimensional images corresponding to each frequency band are further stacked up to form a spatial-temporal-frequency 3-D cube data, based on which we finally extract the characteristic spectrum as the feature of the analyzed optical fiber intrusion signal.

The specific process flow of this method is shown in Fig. 2. Assume that the initial collected optical fiber signal is $s(t,r)$, wherein t presents time and r presents range. A classical technique for time-frequency analysis is the short-time Fourier transform (STFT) as defined by

$$S(f,\tau,r) = \int_{t_1}^{t_2} s(t,r)\cdot w(t-\tau)\cdot \exp\{-j2\pi ft\}dt \tag{1}$$

where f and τ is the frequency and time of intrusion signal, respectively. t_1 is the start time while t_2 is the end time. $w(t)$ is the window function.

For the stationary signals, we can use the STFT for time–frequency analysis. However, if the vibration form is more complex, especially for the non-stationary signals, it requires the multi-resolution analysis. Due to the Heisenberg uncertainty principle [11,12], the time and frequency resolutions of the STFT cannot be improved simultaneously due to the fixed time-bandwidth product. As a bilinear time–frequency analysis, Wigner-Ville distribution (WVD) effectively eliminates the above weakness of STFT with higher time–frequency resolution [13–16]. The WVD of the intrusion signal $s(t,r)$ is mathematically defined as

$$W(f,\tau,r) = \int_{t_1}^{t_2} z(\tau + t/2,r)\cdot z(\tau-t/2,r)\cdot \exp\{-j2\pi ft\}dt \tag{2}$$

where $z(t,r)$ is the analytic associate of $s(t,r)$, which can be expressed as

$$z(t,r) = s(t,r) + j\hat{s}(t,r) \tag{3}$$

where $\hat{s}(t,r)$ is the Hilbert transform of $s(t,r)$, which can be written as

$$\hat{s}(t,r) = (1/\pi)\int_{t_1}^{t_2} s(\tau,r)/(t-\tau)d\tau \tag{4}$$

WVD definition does not include the window function, which can solve the problems caused by window function, and its time-bandwidth product can reach the lower bound given from Heisenberg uncertainly principle. Nevertheless, the existence of cross term in WVD is a shortcoming in the time-frequency analysis. For example, if we use WVD to realize the time-frequency analysis for multi-component signals, e.g., $s(t)=s_1(t)+s_2(t)$, the analysis process will be given as below,

$$\mathrm{WVD}_s(t,\omega) = \mathrm{WVD}_{s_1}(t,\omega) + \mathrm{WVD}_{s_2}(t,\omega) + 2\mathrm{Re}\{\mathrm{WVD}_{s_1s_2}(t,\omega)\} \tag{5}$$

The third item in formula (5) is the cross term as indicated by the existence of negative power for some frequency ranges, and it may has significant amplitude without physical meaning. However, each analyzed signal in this paper is generated by corresponding single intrusion type. Moreover, filtering is also used to suppress the noise as much as possible before the time-frequency analysis. Under these conditions, the influence of the cross term can be almost ignored. For the case of multi-component signals, CWD [17] or TFDS [18] could be considered to suppress the cross term effects. Then, energy band-wise integration on the time-frequency distribution is carried out along the frequency direction to generate spatial-temporal two-dimensional images of each frequency band, which is given by

$$I_i(\tau,r) = \int_{f_i-\frac{\Delta}{2}}^{f_i+\frac{\Delta}{2}} \|W(f,\tau,r)\|_2^2 df \quad i \in [1,L] \tag{6}$$

where f_i is the center frequency of each frequency band, Δ is the bandwidth of each band, i is the index for each band and L is the number of the frequency bands. After that, the two-dimensional image layers corresponding to each frequency band are further formed into the spatial-temporal-frequency 3-D cubic data, which is shown in Fig. 3. This cubic data can be described according to the band order as expressed below

$$\gamma(\tau,r) = [I_1(\tau,r);I_2(\tau,r);\cdots;I_i(\tau,r);\cdots;I_L(\tau,r)] \tag{7}$$

The data represented by Eq. (7) can be further integrated along the direction of frequency band to obtain a full band image, which can be