Signal discrimination with wavelet algorithm and Pearson correlation-based algorithm in φ-OTDR systems

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Abstract: This paper presents a novel method of distinguishing signal, the way expected to reduce the nuisance alarm rate since the high nuisance alarm rate will restrict the capability of phase-sensitive optical time-domain reflection technology. The proposed method includes two parts: wavelet positioning mutation to obtain the perturbation area and Pearson correlation algorithm to directly convert the intensity of the perturbation into a useful amplitude. This technique avoids the use of irrelevant data in these differential signals and provides a simple and feasible new approach for distinguishing signal and optimizing the positioning speed of φ-OTDR systems.

1. Introduction

In recent years, the phase-sensitive optical time-domain reflectometer (φ-OTDR) has attracted much attention because of the capability of being a fully distributed vibration sensor[1]. Due to the φ-OTDR system’s advantages of anti-electromagnetic interference, corrosion resistance, high sensitivity, wide dynamic range. The φ-OTDR provides a wide range of applications such as the health monitoring of large-scale structures, including borders, bridges, tunnels, oil, and gas pipelines[2], ensuring railway safety and perimeter security[3]. However, high nuisance alarm rates and missing alarm rates in φ-OTDR systems greatly restrict the practical applications. Therefore, effectively distinguishing signals can expand the application of φ-OTDR to a broader range of fields.

As the rate of nuisance alarm increases, a system’s perceived reliability decreases, so to reduce the nuisance alarm rate, the researchers proposed various methods to enhance and improve both the detection sensitivity and the classification accuracy of different perturbations, explored by reducing noise, but need for acquiring too many traces. Qin et al., adopted a wavelet denoising method to reduce environmental noise[4]. Lu et al., introduced a heterodyne detection and a signal processing scheme that uses moving average and moving differential to improve the signal-to-noise ratio (SNR)[5]. For the improved classification accuracy of different perturbations, Adeel et al., were able to use fewer acquired traces by utilizing a correlation-based algorithm to improve the possibility of recognizing ephemeral events[6]. T. Q. Sun et al., improved both classification accuracy and computational cost, but a large number of traces need to be acquired to detect a single activity[7]. Other, obtained more comprehensive information about disturbances by multiplexing the φ-OTDR with other sensors. Zhang et al., proposed that the multiple multiplexing systems based on a φ-OTDR combined with a Mach–Zehnder interferometer can also be used to reduce the nuisance alarm rate[8].
However, combining with other sensors increases the complexity of the system and will cause other nuisance alarms.

In this paper, we propose a method to locate and identify the external disturbance quickly. We use wavelet location mutation to obtain the perturbation region, in the disturbance area the Pearson correlation algorithm is used to directly convert the intensity of the perturbation into a useful amplitude to distinguish the signal. Through the above steps, most of the sensing points along the optical fiber that is not related to external disturbance are excluded, and the disturbance-related information is retained, which significantly reduces the data load of signal processing, thereby distinguishing signal. Therefore, this method can be applied to long-distance optical fiber sensing.

2. Methodology

Generally, φ-OTDR obtains information about the vibration signal from the trace of Rayleigh backscattered light intensity, and the rayleigh backscattering in optical fiber is regarded as one-dimensional impulse response model, assuming that a coherent lightwave with a pulse width of \( w_p \) is injected into the sensing fiber, the electric field of the backscattering signal received at \( E(t)_{z=0} \) can be expressed as[9]:

\[
E(t)_{z=0} = E_0 e^{(-2i\omega t)} e^{i(q\omega t)} \sum_{i=0}^{N} r_n e^{i\varphi_n} \tag{1}
\]

Where \( z \in [(tv_g - w_p)/2, tv_g / 2] \), \( v_g \) is the group velocity and \( r_i \) is the reflectivity of each scattering center. \( \varphi_n \) is the phase introduced in the reflected field by the optical path and scattering center. The amplitude of the reflected field will follow a Rayleigh distribution. The normalized intensity \( I \) received at the extreme of the fiber, neglecting the losses, will therefore be:

\[
I = |E|^2 = \left| \sum_{n=1}^{N} r_n e^{i\varphi_n} \right|^2 = \sum_{n=1}^{N} r_n^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} r_ir_j \cos(\varphi_i - \varphi_j) \tag{2}
\]

Obtain the differential signal by subtracting the previous trace:

\[
\delta_i(n) = I_i(n) - I_{i-1}(n) \tag{3}
\]

If a perturbation is introduced at the \( q \) (\( q \in [1, N] \)) scattering center with a corresponding phase perturbation of \( \Theta_p \), then in the perturbation regions, by equation (3), the differential signal between any two traces which under a single the umbrella of a pulse without considering its drag along the fiber can be expressed as:

\[
\delta = 2 \sum_{i=1}^{q-1} \sum_{j=q}^{N} r_ir_j [\cos(\varphi_i - \varphi_j) - \cos(\varphi_i - \varphi_j - \Theta_p)] \tag{4}
\]

When the pulse traverses the perturbation area, the summation effect of the BRS signal on the entire resolution unit changes with the change of each \( n \) in equation (4), but in addition to the region with strong coherence, its response of changes about fiber length is almost constant at all times, so it is not conducive to distinguishing signals. We propose to use wavelet location mutation to obtain the perturbation region, and then use a correlation algorithm to differentiate the different perturbation sources for the differential signal. The Pearson correlation coefficient of the adjacent data vector \( \delta \) can be expressed as:

\[
r(\delta_i(n), \delta_i(n+1)) = \frac{\sum (\delta_i(n) - \overline{\delta_i(n)})(\delta_i(n+1) - \overline{\delta_i(n+1)})}{\left[ \sum (\delta_i(n) - \overline{\delta_i(n)})^2 \sum (\delta_i(n+1) - \overline{\delta_i(n+1)})^2 \right]^{1/2}} \tag{5}
\]

Where \( \delta_i(n), \delta_i(n+1) \) represents the adjacent data vector calculated through the slid window.
3. Experimental setup and results
The experimental setup of a direct detection φ-OTDR system is shown in Figure 1, a narrow-linewidth laser with a center wavelength of 1550 nm, linewidth less than 0.1 kHz is used as a continuous light source. An acoustic-optic modulator (AOM) driven by a pulse generator modulates the continuous light into light pulses with a repetition rate of 10Hz. The optical pulse sequences are amplified by an erbium-doped fiber amplifier (EDFA) and then injected into the sensing fiber through a circulator, the Rayleigh-backscattered light which back from the sensing fiber passes through the circulator again and is then detected by a photodetector (PD), collected by the data acquisition card (DAQ), and then processed by computer.

![Figure 1. Schematic diagram of the direct detected φ-OTDR experimental setup.](image)

Firstly, use a wavelet to extract the location. We apply a sinusoidal signal with a frequency of 100 Hz and an amplitude of 5 V to the PZT, and use equation (3) and equation (4) to obtain the difference of the signal. The result is shown in Figure 2.

![Figure 2. By wavelet to extract mutation location or mutation region for a sinusoidal signal with a frequency of 100 Hz and an amplitude of 5 V is applied to the PZT.](image)

From the analysis of Figure 2 results, we decompose the wavelet into three layers, can see that the location of the perturbation is consistent with[10]. Secondly, use the Pearson correlation algorithm to process the data vectors and distinguish the signals. We apply three sinusoidal signals with a frequency of 100 Hz and different amplitudes to the PZT, and take 5000 traces. The following Figure...
Figure 3. Shows the result of not using the correlation algorithm on three different amplitude of sinusoidal signals with 100 Hz frequency.

From Figure 3, we can conclude that if we have an in-depth understanding of differential data, we can see that there are too many levels close to zero, and few levels are non-zero. Therefore, it is difficult to distinguish the signals. Figure 4 is the result of processing the data vectors using the correlation algorithm, showing an increase in correlation among data-vectors within the resolution cell of spatial points between 40 and 75 against a spatial resolution and the gauge length each with the length of 10m. Each spatial point represents the resolution of a DAQ card with a speed of 250MS/s.

Figure 4. Shows the result of using the correlation algorithm on three different amplitude of sinusoidal signals with 100 Hz frequency.

Figure 5. Experimental results with real vibrations, walking, and running activity.

Figure 5, this is the result that applied two real perturbations of running and walking on the optical fiber and used the proposed method to distinguish the two signals. We calculated 100 spatial points using the proposed method, clear that the proposed method can perform different perturbations distinguish, so the proposed by us distinguishing signal in two steps is effective.

4. Conclusions
We propose a signal discrimination method based on direct detection of the φ-OTDR system to improve the ability to locate and distinguish external perturbations and expect to use reducing nuisance alarm rates. The proposed method is divided into two steps: wavelet extraction mutation region and Pearson correlation algorithm to directly convert the intensity of perturbation into useful amplitude to distinguish the signal. Through the proposed method, most of the sensing points that
provide worthless information are excluded, and the information related to the perturbation is retained, which reduces the cost for signal differentiation. Experiments show that this method can distinguish between different perturbations, easy to use and reduce the nuisance alarm rate in the field of pattern recognition usefully, and can be compatible with a variety of coherent φ-OTDR systems. Besides, it can be fully utilized in such demanding real-time situations as train tracks, power grid monitoring, and security.

Acknowledgments
Authors wishing to acknowledge to M. ADEEL, from Hong Kong Polytechnic University and his team provides data, acknowledge assistance or encouragement from Professor Yu, from School of Automation, China University of Geosciences, Wuhan.

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