Compression and Enhancement of Multiscale Vibration Signals Based on Φ-OTDR

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Abstract. Phase optical time domain reflection (Φ-OTDR) is a distributed optical fiber sensing technology. Its output data contains amplitude, time and other information, so it can accurately reflect various abnormal events. However, due to the high sampling frequency and the large number of sampling points, the amount of data of the vibration signal outputted by it is huge. In order to facilitate the analysis of signal features and optimize the storage space of data, this paper combines Fast Fourier Transform and multi-scale detail enhancement to enhance the vibration signal features while realizing the vibration signal compression.

1. Introduction
As a typical technology for monitoring distributed vibration, Φ-OTDR has been widely used in the fields of large-scale building structure health monitoring [1] and perimeter security in important places [2]. The fiber data collected by the Φ-OTDR consists of time, length, and amplitude, and thus generates a large amount of data. Under different conditions, the fiber signal data is quite different, and the original signal image is difficult to identify the signal. Converting optical fiber signals into images has the advantages of small data volume and clear signal features, so it plays an important role in the application of fiber vibration signal identification and positioning. For image-based processing of signals, a digital nuclear signal processing method is proposed in [3], but the difference between nuclear signal and fiber-optic signal is large. The method of extracting image template adopted in this paper is not applicable to fiber-optic signals. A technique based on the combination of gray image histogram equalization and gradient method is proposed, and a two-dimensional gray image of coherent signal is constructed [4]. The Fast Fourier Transform can be used to convert the fiber signal from the time domain to the frequency domain [5].

And to enhance the features of the signal, Li et al. proposed an EMI signal feature enhancement method based on extreme energy difference and a deep auto-encoder [6]. Tu et al. put forward a vibration separation method by analyzing the time difference between two fiber positions [7]. However, these methods only enhance the feature from the perspective of the signal. At present, it is a more effective method to enhance the signal characteristics from the perspective of image processing. Zhou [8] and Young bae Kim [9] improve the detail features of the image by using the fusion multi-feature and the desired gray level difference of the two pixels, respectively.
In summary, this paper compresses the $\Phi$-OTDR fiber signal and enhances the signal features based on image processing. First of all, $\Phi$-OTDR is used to collect the fiber signal data under different conditions, and the two-dimensional vibration signal is converted into an image by Fast Fourier Transform to reduce the amount of signal data. Then, the multi-scale Gaussian matrix [9] is used to enhance the features of the vibration signals in the image based on the contrast of the image. Finally, it compares the amount of data before and after signal compression, and uses Brenner gradient function [10], Laplacian gradient function [11], gray variance function [12] and gray variance product function to verify the quality of enhanced signal image.

2. Theories

The fiber data collected by $\Phi$-OTDR consists of time, length and amplitude, and the amount of data is huge. Under different conditions, there are still many difficulties in processing fiber signal data because it varies widely. Converting the fiber signal into an image which has the advantages of small data volume and clear signal features, and the processed data can be applied to the identification and positioning of the fiber signal.

2.1. Time domain image of fiber vibration signal

In the industrial field, the fiber vibration mode monitored by the $\Phi$-OTDR technology represents the inherent vibration characteristics of the structure. Each vibration mode has a specific natural frequency, damping ratio and mode shape, which plays an important role in safety monitoring and fault detection. The vibration data collected by the $\Phi$-OTDR technology includes dimensional data such as time, length and amplitude, so it cannot be directly used to describe the vibration mode of the fiber. Therefore, there have been some distributed vibration data needs to be further studied.

Distributed vibration data consists of time, length and amplitude. When a regular round-trip motion is applied to the fiber monitoring point, a regular signal fluctuation image is displayed on the "time-amplitude" plane. The color distribution of the signal in the image ranges from blue to red. And the brighter the color, the stronger the signal. Applying friction and dielectric resistance or other energy to the fiber monitoring point will cause the amplitude to decay over time, which in turn will display a signal image that decays over time in the "length-amplitude" plane.

In order to ensure the accuracy of signal analysis, the amount of data of the vibration signal collected by the phase optical time domain reflectometer is usually large. The size of the vibration data is determined by the sampling rate, spatial point, sampling time, and accuracy. The sample rate defines the number of samples extracted from a continuous signal per second and composed of discrete signals in Hertz (Hz). The spatial point refers to the artificially selected detection point for detecting the vibration signal of the fiber under test. Double-precision floating-point numbers (8 Bytes) are a type of data used by computers that can be used to represent 15 or 16 significant digits in decimal. Taking the sampling rate of 40000 Hz as an example, 100 detection points are selected, the sampling time is 10 s, and the data size is 10.5 MB. The data collected by the data size has 4,000,000 values. The use of signal processing to analyze vibration signals is not suitable for long-fiber, fully distributed fiber-optic signal detection because of the long processing time.

The acquired vibration signal can be converted into a time domain by Fast Fourier Transform and displayed by an image, which can reflect the strength of the signal. The signals in the time domain are in the coordinate system of amplitude and time. The Fast Fourier Transform of the vibration signal can be expressed as.

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-j2\pi nk/N}, \quad k = 0, \ldots, N - 1$$

In the original data, the signal data occupies 359MB of memory. After being converted into a time domain image, the image size is only 143 KB, and the amount of data is significantly reduced. The red dot in the image represents the maximum value of the vibration signal, the blue dot represents the minimum value of the vibration signal, and the imaged signal has significant signal features. Since the
data collected by the Φ-OTDR contains time and amplitude. Using time as the horizontal axis and amplitude as the vertical axis, the fiber signal can be converted from two-dimensional data into an intuitive time-domain signal image. For example, an image of a digging signal with a sampling frequency of 4000 Hz, a sampling point length of 1 km, and a sampling point of 100 is converted into a time domain as shown in Figure 1.

![Figure 1. Time domain image of the digging signal.](image)

2.2. Multi-scale based signal image enhancement

This paper proposes a multi-scale detail enhancement method for fiber optic vibration signals based on the literature [9], which can improve the signal features of time domain images. First, three different Gaussian kernels are employed to blur the input image I and then produce three blurred images which named I_1, I_2, and I_3, respectively. Among them, according to the features of the fiber signal, the standard deviations of the three Gaussian kernels G_1, G_2, and G_3 are 1.0, 4.0, and 8.0, respectively. Secondly, it obtains three different levels of image details,

\[
\begin{aligned}
D_1 &= I - I_1 \\
D_2 &= I - I_2 \\
D_3 &= I - I_3 
\end{aligned}
\]  

(2)

And finally, it can obtain the output image O which enhanced by these three details,

\[
O = (1- \omega_1 \times \text{sgn}(D_1)) \times D_1 + \omega_2 \times D_2 + \omega_3 \times D_3
\]

(3)

Where in order to adapt the fiber signal, \( \omega_1, \omega_2 \) and \( \omega_3 \) are fixed to 0.5, 0.5 and 0.5, respectively. The signal feature images before and after enhancement are shown in Figure 2.

![Figure 2. Comparison of signal features before and after multi-scale enhancement.](image)

From Figure 2, there is a significant difference between (a) and (b), and the enhanced signal image is more distinctive.

3. Experiments

The experiment in this paper can be divided into two parts. The first part is to compare the amount of data of the vibration signal before and after compression. The second part is to verify the quality of the
enhanced signal image by using Brenner gradient function, Laplacian gradient function, gray-scale variance function and gray-scale variance product function.

3.1. Comparison before and after signal compression

In order to verify the effectiveness of signal compression, it collected three different types of fiber vibration signals for tapping, digging and drilling as a comparison. The amount of data before and after compression of the three types of signals is as shown in Table 1.

| Type       | Tapping | Digging | Drilling |
|------------|---------|---------|----------|
| Original signals | 115MB   | 72MB    | 110MB    |
| Compressed signals | 334KB   | 80KB    | 168KB    |

As shown in Table 1, the signal data size converted into image form is reduced by 99.7%, 99.9%, 99.9%, and 99.6%, respectively, compared with the original mapping, digging, and drilling signals.

3.2. Comparative experiments of multi-scale enhancement of signals

For enhanced signal images, a multi-scale approach is applied to the image for enhancement of the signal features. After the original signal image is processed by three different Gaussian kernels, a more distinctive signal image can be obtained. In order to evaluate the image quality before and after enhancement from an objective perspective, this paper introduces no-reference image quality evaluation. The Brenner gradient function, the Laplacian gradient function [11], the gray-scale variance function [12] and the gray-scale variance product function [13] are commonly used in the evaluation of non-reference image quality.

The Brenner gradient function (BG) represents the square of the gray difference between two adjacent pixels. The function is defined as follows,

$$D(f) = \sum_{x} \sum_{y} |f(x+2,y) - f(x,y)|^2$$  \hspace{1cm} (4)

Where $f(x, y)$ represents the gray value of the pixel $(x, y)$, and $D(f)$ is the result which calculated from image sharpness.

The Laplacian gradient function (LG) uses the Laplacian operator to extract the horizontal and vertical gradient values, respectively. The function is defined as follows,

$$D(f) = \sum_{x} \sum_{y} |G(x,y)| \quad G(x,y) > T,$$

$$L = \frac{1}{6} \begin{bmatrix} 1 & 4 & 1 \\ 4 & -20 & 4 \\ 1 & 4 & 1 \end{bmatrix}$$  \hspace{1cm} (6)

Where $T$ is the edge detection threshold, $L$ is Laplacian operator and $G(x,y)$ is the convolution of the Laplacian operator at the pixel $(x,y)$.

The gray-scale variance function (GSV) indicates the degree of gray-scale variation of the image. Since the high-frequency component of the enhanced signal image also increases, the function can effectively calculate the sharpness of the image,

$$D(f) = \sum_{y} \sum_{x} (|f(x,y) - f(x,y-1)| + |f(x,y) - f(x+1,y)|),$$  \hspace{1cm} (7)

The gray-scale variance product (GSVP) function means that the two gray-scale differences of each pixel domain are multiplied and then accumulated pixel by pixel, and the accuracy of the image focus position can be evaluated. The function is defined as follows,
D(f) = \sum_{y} \sum_{x} (|f(x, y) - f(x + 1, y)| \times |f(x, y) - f(x, y + 1)|), \quad (8)

Based on the above four evaluation indicators, this paper evaluates the images of three signals of tapping, digging and drilling. The four types of evaluation methods of the digging signal images before and after enhancement are shown in Table 2.

Table 2. Comparison before and after multi-scale enhancement.

| Type  | Original Image | Enhanced Image |
|-------|----------------|----------------|
| BG    | 239.495        | 300.146        |
| LG    | 370.148        | 604.621        |
| GSV   | 94.992         | 123.532        |
| GSVP  | 64.627         | 113.287        |

The magnitude of the values of the above four methods is positively correlated with the sharpness of the image, thus the meaning of the signal image features can be indicated. By comparing four methods of non-reference image quality evaluation, the enhanced image quality is significantly higher than the original image. Among them, the largest increase is the gray-scale variance product function. The above experiment prove that the signal image enhanced by multi-scale has a better effect than the original image.

4. Conclusion

This paper presents a method for data compression and signal enhancement of fiber optic vibration signals suitable for Φ-OTDR. The vibration signal collected by the Φ-OTDR has the features of high sampling rate and large difference between signals, so the collected vibration signal often occupies a large amount of memory. In the process of analyzing fiber vibration signals, too much data will increase the difficulty and the time complexity of the calculation. The acquired vibration signal can be converted into a time domain image by using Fast Fourier Transform. The intensity of the signal can be expressed in different colors. In order to further enhance the features of the signals in the image, different Gaussian kernels are selected to process the images based on the multi-scale method in this paper. Finally, the paper compares the data size of different types of signals before and after compressions, and four kinds of non-reference image quality evaluation were selected to verify the quality of the enhanced signal image, so that to verify the effectiveness of the proposed method. It has been experimentally proven that the amount of data of the signal is significantly reduced and the enhanced signal image has a higher quality.

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