The Phi-OTDR Signals’ Storage with Image Style

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Abstract. The distributed vibration signal has a large amount of data. It can waste insufficient storage space and have low efficiency of data analysis. Therefore, the paper proposes to save data information in the image format. The images have the original signal feature. The Phi-OTDR is pre-processed by the smooth filter. After the filter, the signal is stored by the image format. The image is extracted by the improved Speeded-Up Robust Features. The signal feature is kept in the image. Then a series of experiments prove the methods effectiveness.

1. Introduction
Phi-OTDR (phase sensitive optical time domain reflect meter) is put forward by Taylor and Lee in 1993 [1]. It serves as a typical technique for monitoring distributed vibrations. At present, it has a wide range of applications in the field of large building structure, health monitoring [2], the perimeter security of important places [3] and so on. Its advantages of distribution are gradually highlighted with the development of the Phi-OTDR technology including the longer monitoring length, smaller monitoring spatial resolution and higher monitoring accuracy. However, these advantages would also bring large amount of monitoring data. The large amount of data not only leads to insufficient storage space but also seriously affects the efficiency of data analysis and processing.

Storage indicates that signals are converted into pictures for storage. The Phi-OTDR signals are simply processed before conversion. For storage research Han S et al. combine the ARMA and SDT method. It compresses the vibration signal on the basis of retaining the characteristic [4]. Malovic M et al. combine the TDE and DPCM method which is used as the entropy coding of pre-processor. It encodes different types of aperiodic signals and also achieves the compression processing of vibration signal [5]. Huang Q et al. propose a lossless compression scheme based on block compression strategy. It combines loss compression and lossless compression which improves the compression performance [6]. Guo W et al. use the vibration signal compression method based on the EEMD. It is effective to decompose the signal component of vibration signal in different frequency bands. It is also called the IMF (Intrinsic Mode Function) method [7]. The compression methods above for vibration signals are almost obtained after analysing and calculating the vibration signals. However, this situation will consume a lot of arithmetic memory. At the same time the compression strategy doesn’t necessarily satisfy all the exceptions. The Phi-OTDR technique collects the distributed vibration signals with two dimensions of time and length. Therefore, the paper references the two-dimensional signal processing techniques in image processing. The signal is directly converted into image to be saved after simple pre-processing of the signal.
In the paper, the vibration signal of Phi-OTDR is pre-processed. The pre-processed signal is stored by the image style. The images include the signal features. According to the image processing, the vibration signal can be detected.

2. The Phi-OTDR Signal Storage with Image Model
The vibration signals monitored by the Phi-OTDR technique are different from the traditional vibration signals. It regards optical fiber as an organic whole for vibration monitoring. In simple terms, monitoring is a vibration signal on a lot of points at the same line [8-10]. Because of the distributed characteristic of the vibration signal of the Phi-OTDR, the vibration signal of the Phi-OTDR contains three kinds of information which are amplitude, time and length while amplitude varies with time and length. In practical engineering, the amount of vibration signal monitored by the method of Phi-OTDR is very large. For example, NBX-S3000 in Japanese Neubrex Corporation is a distributed vibration monitoring equipment. The monitoring indexes are 4K sampling rate, 0.1 meter spatial resolution and 10 meter range. The data storage format is double precision floating-point format. The amount of data generated per second is about 3.2M. The amount of data in 1 days/24 hours is 270G.

2.1. Signal Pre-Processing
Before the image is generated by the Phi-OTDR signal, it is necessary to pre-process the image. The steps are as following.

- Step 1: Because of the characteristics of the acquisition card, the signal will appear a slow and low amplitude sine wave in the process of collecting the Phi-OTDR signal. Therefore, a high pass filter is added to the signal and the threshold value of filter is 1Hz.
- Step 2: The signal processed in step 1 is filtered by a glide window filter. The noise can be effectively smoothed and the possible error points are smoothed. The window value of sliding window filter is usually 10Hz.
- Step 3: The signal processed in step 2 is exponentially magnified. The amplified signal has better signal to noise ratio.

2.2. Storage with Image Style
The pre-processed signals are stored in an image model. The approach is intended to save storage space. The steps are as following.

- Step 1: The distributed vibration signal is cut into one second signals.
- Step 2: The time is at the horizontal axis of the picture and the length is at the longitudinal axis of the picture. The normalized amplitude of the signal corresponds to the gray value from 0 to 1.
- Step 3: In the generated image, the number of pixels on the horizontal axis ($\text{Pixel}_x$) is the number of sampling points per second. It is also called sampling rate ($F_S$) as shown in equation (1). The natural frequencies of large structures are from 0 to 60Hz. According to Nyquist's law, the sampling rate should reach 120Hz at least. The frequency range of impact signals of cement concrete structures is concentrated from several hundreds to more than one thousand and more Hz, so the sampling frequency is about 1K-4KHz.

$$\text{Pixel}_x = F_S$$  \hspace{1cm} (1)

- Step 4: In the generated image, the number of pixels on the vertical axis ($\text{Pixel}_y$) is the ratio of length ($L$) and space sampling rate ($R$). It is shown in equation (2).

$$\text{Pixel}_y = \frac{L}{R} * 20$$  \hspace{1cm} (2)

- Step 5: The image is saved into .jpg or .bmp format.
2.3. Feature Extraction by Surf

Surf is the abbreviation of "Speeded-Up Robust Features". The operator solves the shortcoming of high computational complexity and long time consuming of Sift on the basis of the excellent performance of Sift operator. It not only improves the extraction of interest points and the description of feature vectors, but also improves the computing speed [19-20]. The Surf method is mainly divided into five steps. They are constructing Hessian matrix, calculating eigenvalue, constructing Gauss Pyramid, determining principal direction of feature point, locating feature point and constructing feature descriptor. Among the steps, the most important one is the box filter. The classical Surf method is inspired by the DOG operator approximation LOG operator in the SIFT method. The box filter simplifies and approximates the Hessian matrix. Then the two order Gauss template is segmented by it. The white and weak white regions approximate the white region. The black and weak black regions approximate black areas in the box filter. It could increase the speed but lose accuracy. The improved box filter solves the problem. Traditional box filter includes three values which are 1 (white), 0 (gray) and -1 (black). The improved Surf includes five values which are 1, 0.5, 0, -0.5 and -1. At the same time the proportion of regional areas increased needs to ensure consistency as shown in Figure 1.

![Figure 1. Improved box filter.](image)

3. Experiments

The Phi-OTDR instrument in this paper is the NBX-S3000 instrument from the Japanese Nebrex company. The instrument is shown in Figure 2.

The actual parameters of the device are as follows.

1. Sampling rate: 4000Hz.
2. Recording time: 10s.
3. Spatial resolution: 0.1m.
4. Recording distance: 10m.

The Phi-OTDR signal is a distributed signal. It contains information about the length axis and the time axis. The schematic diagram of a signal is show in Figure 3.

![Figure 2. Physical picture of Phi-OTDR instrument.](image)
The vibration signal acquired by Phi-OTDR is stored by the image style. The specific image of each step is shown in Figure 4.

As you can see in Figure 4, there are several points as following.

1. In Figure 4(a), it is obvious that the original signal is transformed into an image and the signal is not very obvious.
2. In Figure 4(b), the signal generated by the filtered signal is clearer and the noise becomes almost white background.
3. In Figure 4(c), the signal generated by the enhanced signal is perfect and the signal is clear and obvious.

Several signal filter methods have been operated in this paper. The filtering method in the paper is better than other mainstream filtering methods in terms of SNR and efficiency. The comparison results are shown in Table 1.
Table 1. Comparison of filtering effects among various methods.

| No. | Name                   | Average SNR(dB) | Time(s) |
|-----|------------------------|-----------------|---------|
| 1   | The method in the paper| 5.0422          | 6.78    |
| 2   | Wiener filter          | 4.6231          | 12.71   |
| 3   | Kalman filter          | 4.8672          | 11.18   |
| 4   | Adaptive filter        | 4.4517          | 14.31   |
| 5   | Wavelet filter         | 4.9951          | 16.14   |

Table 1 shows that the method in the paper outperforms SNR and efficiency, especially operation efficiency. It saves about 45% time than “Kalman filter”. There are two main reasons for the situation as following. On the one hand, the monitored signal is the mechanical damped vibration signal. The characteristics of the signal are relatively simple and it is easy to handle. On the other hand, it is very time-consuming to deal with distributed vibration signals on the each length point. At the same time, its SNR may be strong or weak. The strong signal and the weak signal are unsuitable some advanced methods at the same time.

About memory space saved by transforming the signal into image, a series of experiments are carried out. The results are shown in Table 2.

Table 2. Comparison of data file sizes in different formats.

| No. | Data format | Time | The number of files | The size of single file | Total | Compress by rar |
|-----|-------------|------|---------------------|------------------------|-------|-----------------|
| 1   | .mat        | 10s  | 1                   | 604MB                  | 604MB | 312 MB          |
| 2   | .csv        | 10s  | 1                   | 451MB                  | 451MB | 229 MB          |
| 3   | .bin        | 10s  | 1                   | 367MB                  | 367MB | 190 MB          |
| 4   | .jpg        | 10s  | 20                  | 16.6KB                 | 352KB | 189KB           |

From the Table 2, saving data by picture format can greatly reduce the memory size. The memory of picture file is reduced about 1000 times memory of binary file. Therefore, it has a good effect on the massive data produced by the Phi-OTDR technology, and has decisive significance in the actual engineering application. There are two main reasons for the result. Firstly, the data in the files like “.csv” and “.mat” is usually stored in double precision floating-point number style. The data in the image is stored in the integer style. Secondly, the format space of the image file is smaller than other files.

The following groups of experiments are about vibration source. They verify the effect of image preservation on signal characteristics. The vibration source uses standard vibratory equipment. Figure 5 is a physical picture of five percussion hammers on the knocker. In order to restrain the environmental noise and ensure the good vibration effect, the anechoic chamber is selected to test.

![Figure 5](image)

Figure 5. A physical picture of five hammers on a knocker.

Figure 6 shows that a sketch of effect for single point knocks on the fiber. The vertical intersection point between vibration source and optical fiber is the strongest point of vibration.
Figure 6. Perceptual model on length axis.

There are five hammer hammers with equal intervals on the knocker. The striking distance between two strikes is 10cm. Therefore, the four distances between the center points of the five target signals can be obtained by image processing method. The image processing methods are compared with other traditional signal processing methods which are FFT, HHT and WT. The distance contrast of each interval is shown in Table 3.

Table 3. Tracing effect of vibration sources between different methods (cm).

| No. | Name | Interval No.1 | Interval No.2 | Interval No.3 | Interval No.4 |
|-----|------|---------------|---------------|---------------|---------------|
| 1   | Surf | 10.83         | 10.71         | 11.14         | 9.11          |
| 2   | FFT  | 10.78         | 10.69         | 11.11         | 9.18          |
| 3   | HHT  | 10.75         | 10.65         | 11.04         | 9.21          |
| 4   | WT   | 10.76         | 10.67         | 11.08         | 9.22          |

From Table 3, the mode of image source tracking is basically the same as the traditional method. The positioning error is about 1.8% lower than that of traditional method. The positioning error is about 5% by traditional methods and the positioning error is about 5.1% by the method in the paper. Such accuracy falls within acceptable limits in practical engineering. The error can be neglected in engineering and hardly affect location. The point perpendicular to the fiber is the strongest point of the vibration signal. The signal intensity decreases from the centre of the vertical point to the two ends of the fiber. In the process of signal recognition on one frame, there is little error in the recognition of the target signal but the error will be corrected over time. Therefore, even if the storage and process of signal is referenced the image style, the tracking effect of the vibration source is also very good.

4. Conclusion
In this paper, the problem is the storage of a Phi-OTDR signal with image model. The research and main conclusions are as follows.

(1) The distributed vibration signal can be transformed into image storage. It can greatly reduce the memory space.
(2) For vibration signal under monitoring technology, the filtering method is better.
(3) The stored picture preserves certain signal features.

Fully distributed optical fiber sensing technology has broad market demand and great potential for development. Phi-OTDR is an important member of them. In the Phi-OTDR technology, it’s a trend in the future that Phi-OTDR signals is dialed with image style. It makes Phi-OTDR technology to have better performance, smaller memory, shorter computing time, simpler operations and brighter prospects. The main research work of this paper is the mechanical damping vibration signal. But there are many kinds of complex situations in actual conditions. And there are also many types of Phi-OTDR signals in the future research. In order to make the theory more representative and universal, we will study the non-damped vibration signals such as leakage signals in the future.
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