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Application of wavelet analysis in underground embedded distributed optical fiber vibration monitoring system

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Abstract: The distributed optical fiber vibration monitoring system is often used for intrusion detection in the area. Usually, the optical fiber cable is buried in 10 to 30cm or in the net type installation. When the surface is passed, it can locate its position accurately. The system is sensitive to the micro vibration, and the optical fiber vibration can be detected even by the small wind load. The distributed optical fiber vibration monitoring system can realize the on-line real-time monitoring of the vibration response of the dam. The system obtains the external vibration information by detecting the light intensity, phase, polarization state and other information of the reflected light signal of the echo. The captured signals are mostly short-time pulse signals, and the real-time processing ability of the system for the signal is required. At the same time, the vibration signal is manifested by the singular point mode of sudden change. Therefore, the feature extraction of the optical signal can be realized by the efficient singular point detection ability of the wavelet analysis. At the same time, the real-time and accuracy of the data processing can be greatly improved compared with the conventional cumulative average de-noising method. The accuracy of the domestic vibration measurement system can reach 50m. In this paper, the accuracy of the vibration measurement system can be improved to 15m by studying the algorithm.

1. Introduction:
With the development of our country’s economy, all kinds of precious resources have been excavated in succession. New technology and patent emerge in an endless stream, just as some national-level patent and technique in particular and such technique is generally relevant to national security and development. Therefore, it needs to be monitored against technical intrusion. In the meantime, with part of regions’ development of mining technology, inevitably, someone will stretch out their greedy hand once plenty of scarce resources get their attention. Hence we need to monitor these regions which involve national security or scarce resources, in order to resist artificial intrusion.

Optical Time Domain Reflection Technology had applied to monitor the loss characteristics of optical fiber since Dr. Barnoski proposed it in 1976. KongliXie¹ , from University of Electronic Science and Technology of China, proposed and constructed
distributed optical fiber sensing system based on high power through study $\phi - OTDR$ system in 2008; In 2009, Jianfeng Yue\cite{2} of UESTC realized optical fiber sensing vibration measurement system with a positioning range of 12km and a signal-to-noise ratio of 5db through the research system; In 2013, Xueyi Chen\cite{3} Etc. realized the monitoring range of the system reaching 35km and the spatial resolution of 15mthrough studying a distributed optical fiber sensing system based on dry backward scattering Rayleigh; In April 2016, Yan Zhang\cite{4}, from School of Electronic Information Engineering, proposed a signal recognition method based on special parameters by studying the distributed optical fiber perturbation sensing system; In 2017, Dong Qi\cite{5}designed the distributed optical fiber vibration measuring instrument based on the principle, which can be applied to vibration parameter monitoring of track, pipeline and long-distance civil construction. Based on Rayleigh Scattering Technology, we could do a vibration survey and achieve accurate positing by using the distributed Rayleigh scattering optical fiber vibration measurement system. Due to the system by capturing short pulse signal to locate capture, its ability to real-time signal is higher, at the same time, detecting vibration signals through the form of a singular point, in a concise and clear way.

The Wavelet Analysis Theory started at the beginning of 20th century. In 1910, Haar proposed the theory of orthogonal norm wavelet basis. A.Grossmann and J.Morlet, the French geologist, constructed and named Grossmann-Morlet\cite{6} as Wavelet and then applied it to the analysis of geological statistics in 1984. S.Mallet utilize self-developed multiresolution analysis method\cite{7} to decompose and reconstruct the Orthonormal Wavelets, which formally unified the construction method of Orthonormal Wavelets\cite{8}. Compared with all kinds of studies in the world, there are relatively few researches on Wavelet Analysis Algorithms in China. In 1994, there was a high tide of research on Wavelet Analysis Technology in China. Under such tendency, the applicant of Wavelet De-noising on buildings become far more frequently. Based on this, various kinds of paper technology emerge in endlessly. In 1997, Wavelet Analysis was used to monitor the whole-week hopping of GPS monitoring values by Dingfa Huang and JianchengZuo\cite{9}. Peng Huang\cite{10} etc. had proposed and demonstrated that the selective average threshold algorithm can improve the signal-to-noise ratio of the system through studying the distributed optical fiber perturbation sensing system in 2016. Based on this, Rayleigh Scattering Signal is de-noised by Wavelet De-noising Method in this paper.

2. Experimental Section

2.1 The components and devices of this system

The structure of Distributed Optical Fiber Vibration Measurement System is shown in figure 1

![Figure1](attachment:image1.png)

$\phi - OTDR$ principle diagram

Parts of system components is shown as figure 2
Fiber is extremely sensitive to the vibration signals, so the vibration detection section is buried at a depth of about 10cm in the sand soil. The devices are shown as figure 3. The vibration signals are exerted by artificial pat. Buried in the soil, the impact on fiber can be well shield from the outside world as well as descend the misread rate toward the vibration signals. Although the sensing effect will be reduced, the vibration signal can be clearly distinguished.

2.2 Experimental Methods

The length of vibration measurement fiber used in this paper is 30km, the pulse width of fiber laser is 150 μs, and the system identification precision is 15m by using spatial resolution theory. Firstly, vibration is applied to approximately 9900m and 10200m positions at the same time, appropriate de-noising method is selected, and vibration detection is carried out for about 9500m and 20m in total in the optical fiber. In the process of data analysis, a certain number of scattering curves are selected for the difference between two instantaneous polarization states, as shown in formula 1.

\[
\left[ \frac{[x(i) - x(i-n)]}{x(i)} \right] \quad (1)
\]

Formula 1, the N interval scattering curve on the number of article, such as the corresponding time interval is 0.1 s, n = 2 (accumulative 50 times, pulse cycle is 1 ms), so the value of n for their respective system decides if it is necessary, using formula 1 to overlay graphics mapped, can be convenient to observe the location of the vibration. The reason for the cause of the difference is due to the interval must be inside short time, if a spot at a certain moment in the vibration signal, then the moment the location of the point on the Rayleigh scattering signal and necessarily moment have obvious differences in optical power, and no vibration signal occurred after the location of the point light power difference value is 0, and divided by the number, the result is a relative value, can significantly reduce the power between two collections too much change will affect the signal of the system. It is easy to determine the vibration information of the position point by using this method, so it is necessary to conduct differential processing for the data with a certain time interval.

3. Experiment and discussion

Discrete Wavelet De-noising and Wavelet Packet De-noising are two main commonly ways used in Wavelet De-noising Method. Compared Wavelet Packet De-noising Method with Discrete Wavelet
De-noising Method, which add the decomposition of detail coefficients. Therefore, the Wavelet Packet De-noising Method can decompose the Wavelet coefficient more thoroughly, which is conducive to the elimination of noise. The decomposition structure is shown in figure 4:

![Figure 4](image)

**Figure 4** Example of small wavenumber

Assuming that the original data is the data S, the statistic S can be decomposed into approximation signals A1 and detail signals D1 then through Wavelet Packet Function wpdec, then again decomposition approximation signals A1 and detail D1, A1 is decomposed into approximation signal can be nearly signals AA2 and detail DA2, D1 will detail signal is decomposed into approximation signals AD2 and detail signal DD2, and then can be resolved one after another according to the number of decomposition. The vibration data applied to the vibration at the positions of 9900m and 10200m are analyzed, and the vibration signal was processed offline using Discrete Wavelet De-noising and Wavelet Packet De-noising respectively. The results were shown in figure 5:

![Figure 5](image)

(a)Discrete wavelet de-noising  (b)Wavelet packet denoising

**Figure 5** Comparison of two wavelet denoising methods

From Discrete Wavelet De-noising figure 5 (a) and Wavelet Packet De-noising figure 5 (b), we can see that the vibration signal appears near 9900 m and 10200 m, and the extremum in 9900 m position is $2 \times 10^{-3}$, however, the wavelet packet de-noising is $6 \times 10^{-3}$ after extreme value point; At a distance of 10200, the maximum value of Discrete Wavelet De-noising is $2.5 \times 10^{-3}$, and the Wavelet Packet De-noising is $5 \times 10^{-3}$. So we can come to conclusion that vibration signal De-noising extreme value is larger than the extremum of discrete wavelet de-noising after Wavelet Packet. In other words, the Wavelet Packet towards the identification of vibration signals with higher precision. Thus, the final analyzed statistics need to be de-noised by Wavelet Packet.

The measured Rayleigh Scattering Signal is shown in figure 6, which exerted at the position point of 9500 by artificial pat. We can see from figure 6, the whole system reaches a perspective effect and it can monitor the vibration accurately after covering the fiber in the soil. Although the sensing effect will be reduced, the vibration signal can be clearly distinguished. With the increasing distance of fiber, the ratio of signal noise can be reduced. Thus, it needs to de-noise when dealing with the statistics.
Figure 6 Rayleigh scattering signal

Processing the twice collected statistics by using \( \frac{1}{2} \left( x(2) - x(1) \right) \), the five-point sum of the processed results is carried out, and the absolute value of the sum is extracted, and the data of one difference can be obtained, as the difference statistics shown in figure 7. Because two frames of data were collected at one time during the collection process, the results of two frames of data analysis could be superimposed, the result of the processing is shown in figure 7(b). Through figure 7 we can find that it actually appear surprising fluctuation in the 1900m position. It is in line with the vibration condition given by the working condition, and the actual length is 9500m, which is in line with the position of the vibration signal given by the working condition.

![Figure 6 Rayleigh scattering signal](image)

Figure 7 Difference effect diagram

The data collected by the system at the vibration position point of 9,500m is differentiated, and then the difference data is processed by Wavelet Packet De-noising. The de-noising effect is shown in figure 8(a) (b):

![Figure 8 Image before and after de-noising of wavelet packets](image)

Compared with the order of de-noising, it can be easily found that in the part of vibration signal not applied before de-noising, the fluctuation value of difference ratio of optical power is about 0.1, and after de-noising, it is about 0.02. Therefore, the accuracy of identification after de-noising is improved.
4. Conclusions

1) The accuracy of identifying the vibration signal is up to 15m through de-noising the Wavelet Packet.

2) Wavelet Packet de-noising is more suitable for the system through studying the principle of vibration signal identification for Distributed Vibration Measurement Optical Fiber System and comparing the traditional Wavelet Function, Wavelet Packet, and Wavelet Filtering Effect.

3) Using the combination of C# language and MATLAB SQL Database, the Distributed Vibration Measurement Optical Fiber System Software is developed, which realizes the identification of vibration signals from data collection and analysis.

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