Research on Optical Fiber Sensor Signal Processing Technology Based on Variational Mode Decomposition and Singular Spectrum Analysis

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Abstract. To better apply the phase-sensitive optical time-domain reflectometer (Φ-OTDR) in projects with complex environments, given the problem of the low signal-to-noise ratio of the Φ-OTDR signal, a variational mode decomposition (VMD) is proposed. Signal processing algorithm combined with singular spectrum analysis. First, the equalization optimizer (EO) optimizes the VMD. The VMD decomposes the preprocessed signal into a multi-layer eigenmode function (IMF), selects the IMF component according to the correlation coefficient, and after the SSA noise reduction process, the signal Reconstruction to realize the noise reduction processing of the Φ-OTDR signal. Through experiments, it is proved that the relative mean square error (RMSE) of the method in this paper is lower than that of EO-VMD, and the noise reduction performance is better.

1. Introduction

Φ-OTDR has the advantages of real-time feedback, high sensitivity, wide detection range and flexibility. It has good application performance in oil and gas pipelines, water pipelines and perimeter security. But Φ-OTDR has high sensitivity and is easily disturbed by two kinds of noise in engineering[1-4]. One is the noise during system operation, and the other is environmental noise. The former can be filtered out by traditional methods, while the latter is complex random noise, which is difficult to remove, causing useful signals to drown in noise. Therefore, inhibition of the environmental noise in OTDR is the purpose of this paper.
2. The principle of the noise reduction method

2.1. The principle of variational mode decomposition

Variational Modal Decomposition (VMD) is a signal processing method proposed by Dragmiretskiy K and others in 2014\(^5\). VMD decomposes the original signal into multiple intrinsic modal components (IMF), and the center frequency and bandwidth of each component have adaptively obtained the optimal solution, thereby realizing the effective separation of modal components (IMF).

The constructed variational model is as follows\(^6\)-\(^7\):

\[
\min \left\{ \sum_k \| \tilde{\omega}_k[u_k(t) e^{-j\omega_k t}] \|^2 \right\} \quad \text{s.t.} \quad \sum_k u_k = f
\]

In formula (1): \(k\) is the number of modal layers to be decomposed, \(\delta(t)\) is the impulse function, \(u_k\) is the \(k\)th modal component decomposition, which is subjected to Hilbert transform, Obtain the one-sided spectrum corresponding to \(k\) modal components: \(\tilde{\omega}_k [\delta(t) + \frac{j}{\pi t}] u_k(t)\), \(\omega_k\) corresponds to the center frequency of each modal component decomposition.

2.2. Principle of equalization optimizer

The balanced detector is a metaheuristic algorithm (simulated natural algorithm) proposed in 2020. Inspired by the dynamic mass balance of the control volume, it simulates the process of entry, departure and generation of the inactive components in the control volume. EO algorithm has the advantages of simple structure, strong adaptability and high flexibility\(^8\). The algorithm optimization steps are as follows\(^9\):

1. Initialization: The algorithm performs random initialization within the upper and lower bounds of each optimization variable, as follows:

\[
C_i^0 = C_{\min}^i + \text{rand}((C_{\max}^i - C_{\min}^i), i = 1, 2, \cdots, N)
\]

In equation (2), \(C_{\min}\) and \(C_{\max}\) are the upper and lower limit vectors of the optimization variable respectively; \(\text{rand}\) is a random vector between \([0,1]\); \(N\) is the population number.

2. Balanced state pool: In order to improve the algorithm's global searchability, the equilibrium state \(C_{eq}\) will be selected from 5 current optimal candidate solutions. The balanced state pool formed from these candidate solutions is as follows:

\[
C_{eq,\text{pool}} = \{C_{eq,1}, C_{eq,2}, C_{eq,3}, C_{eq,4}, C_{eq,\text{ave}}\}
\]

3. Exponential term coefficient \(F\):

\[
F = a_i * \text{sign}(r - 0.5)(e^{-\lambda r} - 1)
\]

In the formula (4), \(a_i\) is the weight constant coefficient of the global search; both \(r\) and \(\lambda\) represent random number vectors.

4. Quality generation rate \(G\): In order to strengthen the local optimization capability of the algorithm, the generation rate is designed as follows:

\[
G = G_{cp} (C_{eq} - \lambda C) \quad G_{cp} = \begin{cases} 0.5r_1, r_2 \geq 0.5 \\ 0, \text{otherwise} \end{cases}
\]

In formula (5), \(G_{cp}\) is a vector of generating rate control parameters; \(r_1\) and \(r_2\) are random number vectors, and each element value is a random number from 0 to 1.

5. Solution update: For optimization problems, the solution can be updated as:

\[
C = C_{eq} + (C - C_{eq})F + G(1 - F) / \lambda V
\]

2.3. Principles of singular spectrum analysis (SSA)

SSA is a principal component analysis method, which is used to process nonlinear sequences. It has time-frequency domain feature analysis method and does not need to select structural function as a
priori information, so it can more flexibly analyze nonlinear and unstable time series, to realize functions such as denoising and feature extraction\cite{10}.

The four steps of SSA are embedding, singular value decomposition, grouping and reconstruction\cite{11}.

1. Embedding: The signal collected by Φ-OTDR can be regarded as a one-dimensional time series signal sampled at equal intervals. If the window is embedded, the trajectory matrix $X$ can be obtained.

2. Singular value decomposition: singular value decomposition of the trajectory matrix can obtain singular values of window size. Each singular value can be multiplied by its corresponding empirical orthogonal function and principal component to obtain $X_i$ in the $X = \sum_i X_i$.

3. Grouping: Divide them into useful signals and noises according to their characteristic values.

4. Reconstruction: Ignore the noise, average the useful signal diagonally, and restore the trajectory matrix to a signal.

3. Experimental verifications

The parameters of the Φ-OTDR system used in the experiment are as follows: the laser wavelength is 1550 nm, the line width is 1.66 kHz, the sampling rate of the acquisition card is 250 MSa/s, the sensing fiber length is 40 km, and the spatial resolution is 0.4m.

3.1. Single-point perturbation algorithm verification

Piezoelectric ceramics are used to disturb the optical fiber at 2.35km. The signals at the disturbance are collected and processed by moving average and difference to remove the system noise. After many experiments, it is found that the sliding average and difference results are the best when the sliding window length is 5 and the step size is 8. The preprocessed signal is used as the original signal. The original signal is collected many times to verify the correlation coefficient criterion. In order to measure the noise reduction performance, this paper selects the relative mean square error (RMSE) as the standard, and the relative mean square error is defined as follows:

$$RMSE = \frac{E[(S-Y)^2]}{E[S^2]}$$ \hspace{1cm} (7)

In formula (7), $S$ is the original signal, and $Y$ is the signal after $S$ has been reduced by noise. The smaller the value of RMSE, the better the noise reduction effect. The experiment is shown in figure 1.

![Figure 1 RMSE](image)

It can be seen from the figure that the RMSE of the signal shows a trend of falling first and then rising. When the RMSE is the lowest, the signal noise reduction is the best. Therefore, this paper takes the components with a correlation coefficient lower than 0.4 to perform SSA noise reduction.
processing. The original signal is noise-reduced using the method in this paper, and compared with the noise reduction effect of EO-VMD, the result is shown in Figure 2.

![Figure 2 Single point disturbance](image)

After EO-VMD noise reduction, the RMSE of the signal is 0.3251. Although the signal can be decomposed well, the decomposed components are not processed, resulting in poor noise reduction performance. After noise reduction, according to the method in this paper, the RMSE of the signal is 0.1543, which is better than that of EO-VMD. Therefore, this method can decompose the signal properly, reduce the noise power and remove the noise.

### 3.2. Multi-point disturbance algorithm verification

To verify the noise reduction effect of the abbreviation algorithm in this paper on multi-point disturbance signals, PZT is used for the disturbance at 1.4km and 2.4km of optical fiber. After moving the fiber signal average and difference, noise reduction is carried out by the method in this paper, and compared with EO-VMD. The results are shown in Fig. 3.

![Figure 3 Multi-point disturbance](image)
After EO-VMD noise reduction, the RMSE of the multi-point disturbance signal is 0.3531, and after the noise reduction method in this paper, the RMSE is 0.1324. It can be concluded that the noise reduction in this paper is still effective in the multi-point disturbance.

4. Conclusions
Aiming at the problem of the low signal-to-noise ratio of signals collected by the Φ-OTDR system, a denoising method based on EO-VMD-SSA is proposed. This method uses EO optimized VMD to decompose the signal, then uses SSA to denoise the IMF component with a low correlation coefficient, and then reconstruct it. Through experiments, it is verified that the RMSE of this method after noise reduction is 0.2 higher than that of EO-VMD, which enables the Φ-OTDR system to locate and track interference more accurately.

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