Research on separation technique of DAS signal Based on Variational Mode Decomposition

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***Abstract*—Distributed fiber optic acoustic sensing system (DAS) has been widely used in various engineering applications due to its high sensitivity and long detection distance, However, the actual data is often disturbed by the vibration events in the external environment， which seriously affects the system's ability to recognize Target events. As a result, the collected signal contains multiple vibration event information, resulting in signal aliasing phenomenon, which affects the monitoring effect of the target event. In order to solve the problem that the DAS system is susceptible to signal aliasing caused by the interference of external environment vibration, a variational mode decomposition (VMD) technique is introduced to decompose the actual signal into multiple mode functions (IMF) according to the decomposition parameters to achieve the iteration of the optimal solution of the variational mode pattern, so as to decompose the vibration signal of the target event from the mixed signal. The experimental results show that the VMD method has a good decomposition effect on both the simulated signal and the measured DAS signal.**

Keywords—distributed optical fiber, signal processing, Variational mode decomposition, signal detection

I. INTRODUCTION

Distributed fiber optic acoustic sensing system (DAS) has been widely used to sense external vibration events by demodulating the intensity and phase information of Rayleigh backscattered light in optical fibers to locate and accurately retrieve target vibration events[1-2]. DAS systems have been widely used in perimeter security, oil and gas pipeline monitoring, and structural health monitoring[3-6]. However, DAS systems are susceptible to the interference of external environmental vibration events in practical engineering applications, resulting in the system's missed and false alarm of target events. In order to solve the above problems, a signal separation technique of DAS based on variational mode decomposition is adopted in this paper to achieve effective separation of target events. Firstly, the basic principle of VMD method is introduced. Then, the reliability of the decomposition method is verified by simulation experiments. Finally, the actual signal is collected for verification.

II. PRINCIPLES AND METHODS

Compared with traditional decomposition methods, VMD algorithm extends Wiener filtering to multiple adaptive bands, has better signal decomposition ability, and has unique advantages for non-stationary signals. It can decompose complex signals to obtain multiple modal components, and then obtain disturbance information of target events from it.

The constraint expression of VMD algorithm is shown in (1). The constraint conditions for the optimal decomposition result: 1) The bandwidth sum of the center frequencies of each component is the minimum. 2) The sum of each component is equal to the input signal.

$$\begin{cases} \min_{\{v_k\},\{\omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \\ s.t. \sum_k v_k = S(t) \end{cases} \tag{1}$$

Here， $\{v_k\} = \{v_1, ..., v_k\}$ are K IMFs decomposed by the VMD method， $\{\omega_k\} = \{\omega_1, ..., \omega_k\}$ are the central angular frequency of each IMF component.

In order to calculate the optimal solution of equation (1), the constrained variational problem is transformed into an unconstrained variational problem by introducing Lagrange multipliers $\tau(t)$ and second-order penalty factors α . The conversion result is shown in Equation (2) :

$$L(\{v_k\},\{\omega_k\},\tau(t)) = \alpha \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_k(t) \right] e^{-j\omega_k t} \right\|_2^2 + \left\| S(t) - \sum_k v_k(t) \right\|_2^2 + \left\langle \tau(t), S(t) - \sum_k v_k(t) \right\rangle \tag{2}$$

Finally, the alternating direction method of multipliers is used to iteratively solve each component and its central frequency. The iterative formula of each signal component and its central frequency is as follows:

$$\hat{v}_k^{n+1}(\omega)=\frac{\hat{s}(\omega)-\sum_{i\neq k}\hat{v}_i(\omega)+\hat{\tau}(\omega)/2}{1+2\alpha(\omega-\omega_k)^2} \tag{3}$$

$$\omega_k^{n+1}=\frac{\int_0^{\infty}\omega\left|\hat{v}_k(\omega)\right|^2 d\omega}{\int_0^{\infty}\left|\hat{v}_k(\omega)\right|^2 d\omega} \tag{4}$$

The iterative formula of Lagrange multiplier $\tau(t)$:

$$\hat{\tau}^{n+1}(\omega)=\hat{\tau}^{n}(\omega)+\gamma\left(\hat{s}(\omega)-\sum_k \hat{v}_k^{n+1}(\omega)\right) \tag{5}$$

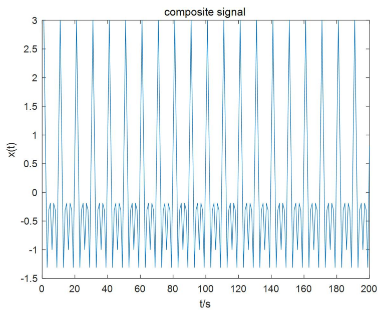
Where, γ represents noise tolerance parameter, and the iteration termination condition is:

$$\sum_k \left\|\hat{v}_k^{n+1}-\hat{v}_k^{n}\right\|_2^2 / \left\|\hat{v}_k^{n}\right\|_2^2 < \varepsilon \tag{6}$$

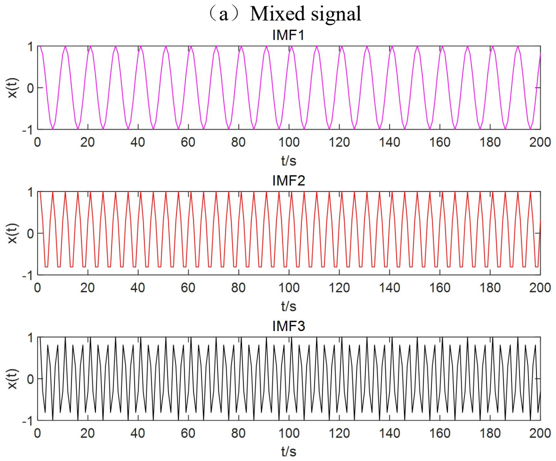
Through the above calculation process, the input signal can be decomposed by VMD method, and different groups of decomposed signals can be obtained, so as to realize the decomposition of mixed signals.

III. Simulation Experiment

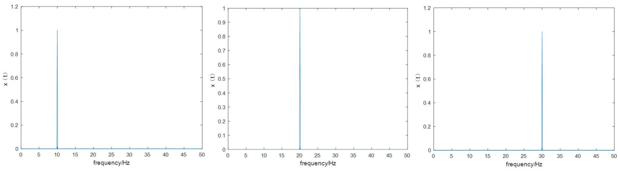
We synthesized 10 Hz, 20 Hz and 30 Hz cosine wave signals as input signals. Then, VMD decomposition was performed on the synthesized signal, and the decomposition results were shown in Fig 1. It can be clearly seen from Figure 1 that VMD algorithm can decompose 10 Hz, 20 Hz and 30 Hz frequency signals independently, which shows that VMD method has good decomposition ability for mixed signals, and no mode aliasing problem.



（a）Mixed signal



（b）Time domain decomposition result



（c）Frequency domain decomposition results

Fig. 1. Mixed signal decomposition results

IV. Measured Data Experiment

In order to verify the decomposition effect of VMD method on DAS signal, a 10km optical fiber is connected to the output end of the DAS system, as shown in Fig 2, and a PZT device is added to the middle position of the optical fiber. The device can be fixed at a certain position of the optical fiber and generate any stable vibration wave to simulate the occurrence of disturbance events along the optical fiber, The PZT is used to generate a set of sine wave signals, and the final detection results are shown in Fig 3. As shown in the figure, the measured signal is a mixed signal, including not only the regular signal generated by PZT, but also the acoustic information caused by the small vibration of the external environment, which is monitored by the DAS system. The measurement signal is irregular. The VMD method has been used to decompose this group of mixed signals, and the decomposition results are shown in Fig 4. It can be seen from the figure that the VMD method can effectively separate the vibration signals of target events from the mixed DAS signals. The regular sinusoidal waveform is extracted.

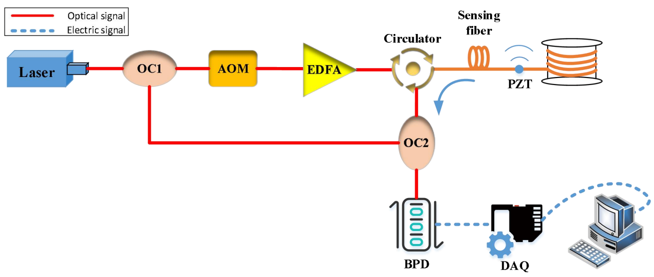


Fig. 2. Experimental system

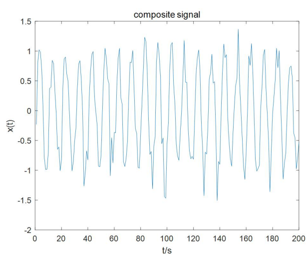


Fig. 3. Experimental results

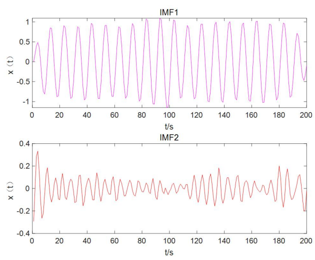


Fig. 4. Decomposition result

V. Conclusions

In summary, in order to solve the problem of signal aliasing in signal acquisition of DAS system, a DAS signal separation technology based on variational mode decomposition is adopted in this paper to achieve effective separation of target events. The experimental results show that the VMD method can show good decomposition effect in both the simulation experiment and the actual experiment, and can improve the practical application value of distributed optical fiber acoustic sensing system.

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