Anchoring Bolt Detection Based on Morphological Filtering and Variational Modal Decomposition

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(Received 8 March 2018; revised 28 December 2018; accepted 15 January 2019)

Abstract: The pull test is a damaging detection method that fails to measure the actual length of a bolt. Thus, the ultrasonic echo is an important non-destructive testing method for bolt quality detection. In this research, the variational modal decomposition (VMD) method is introduced into the bolt detection signal analysis. On the basis of morphological filtering (MF) and the VMD method, a VMD-combined MF principle is established into a bolt detection signal analysis method (MF-VMD). MF-VMD is used to analyze the vibration and actual bolt detection signals of the simulation. Results show that MF-VMD effectively separates intrinsic mode function, even under strong interference. In comparison with conventional VMD method, the proposed method can remove noise interference. An intrinsic mode function of the field detection signal can be effectively identified by reflecting the signal at the bottom of the bolt.

Key words: bolt detection; variational modal decomposition; morphological filtering; intrinsic mode function

CLC number: TU413; TN958 **Document code:** A **Article ID:** 1005-1120(2019)04-0628-07

0 Introduction

A bolt anchoring system is a discreet engineering process and is subject to geological conditions, construction technology, and other environmental aspects[1]. Thus, finding hidden problems is difficult. An acoustic method is an important non-destructive testing method used for bolt detection in civil engineering[2-4]. To obtain an effective signal, the traditional analysis method undergoes a global transformation, either completely in a time or frequency domain. It is particularly suitable for studying stationary signals. To solve this problem, many data processing methods, such as short-time Fourier, Gabor, Wigner-Ville, and wavelet transform, have been proposed[5-9].

Wavelet transform has been adopted in many studies[10-12]. However, the effect of wavelet transform is typically limited by selecting wavelet bases and decomposed layers. The empirical mode decomposition (EMD) can adaptively select a substrate in accordance with the characteristics of signals in a multi-resolution; however, the EMD avoids selecting a wavelet basis[13-15]. Moreover, the EMD faces a modal aliasing problem when processing data.

An ensemble EMD (EEMD) is also proposed for solving the modal aliasing problem that is present in the EMD[16]. However, this technique may produce a false pattern after the decomposition because this method adds a different white noise, which may cause errors[17].

In recent years, the variational modal decomposition (VMD) method has been proposed[18]. This method transforms an input signal into several constraint problems through the Wiener filtering and Hilbert transform. It iterates the center frequency of each component and bandwidth to achieve an adap-

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How to cite this article: XU Juncai, REN Qingwen, LEI Bangjun. Anchoring Bolt Detection Based on Morphological Filtering and Variational Modal Decomposition[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2019, 36(4):628-634.
http://dx.doi.org/10.16356/j.1005-1120.2019.04.009

tive decomposition of the signal. The results show that the method is superior to the traditional EMD method[19-20].

Based on VMD theory, the VMD method is introduced into the bolt detection signal analysis. The principle of morphological filtering (MF) is combined with VMD, another method (i. e., MF-VMD) is proposed, and an MF-VMD analysis method is established. MF-VMD is used to simulate vibration signals and process the actual Bolt detection signal to verify its effect. This research promotes the theory of bolt quality detection and detection effect of bolts and provides a scientific decision-making basis for the construction and management of anchoring geotechnical engineering.

1 Theory and Methodology

1.1 MF principle

MF is achieved through a segmenting element that is moving in a signal to extract the information of a signal, maintain the details of the signal, and remove the purpose of noise interference. MF is generally achieved by expansion, corrosion, opening, and closing operations. If one vibration $s(n)$ has N sampling points, the segmenting element $g(m)$, $m=0,1,\cdots,M-1$, and expansion and corrosion operations with $s(n)$ to $g(m)$ can be defined as

$$\left(s\Theta g\right)(n)=\min_{m}\left\{s(n+m)-g(m)\right\} \quad (1)$$

$$\left(s\oplus g\right)(n)=\max_{m}\left\{s(n-m)-g(m)\right\} \quad (2)$$

Opening and closing operations with $s(n)$ to $g(m)$ can be defined as

$$\left(s\circ g\right)(n)=\left(s\Theta g\oplus g\right)(n) \quad (3)$$

$$\left(s\cdot g\right)(n)=\left(s\Theta g\oplus g\right)(n) \quad (4)$$

In practical applications, the open-closed and closed-and-open combined morphological filters are constructed using a cascade form, which is used for noise reduction of vibration signals. The expression is as follows.

$$\mathrm{MMC}(s)=\left(s\circ g\cdot g+s\cdot g\circ g\right)/2 \quad (5)$$

The effect of MF depends on the selected morphological operation and is related to the structural elements that are used. A vibration signal is filtered by the elements of a linear structure, and the correlation between the acoustic signal before and after the filtering is considered a criterion of the selection width value in this research.

1.2 VMD principle

VMD is a variational problem. To minimize the sum of the estimated bandwidths of each mode, it is assumed that each mode has a finite bandwidth with different central frequencies. Consequently, an alternating direction multiplier method has been adopted to constantly update the mode and its central frequency, with the mode being gradually demodulated to its corresponding baseband. Then, the final mode and the corresponding center frequency are extracted.

If a signal S_0 is decomposed into N intrinsic mode function (IMF), the solution for the corresponding variational problem can be expressed as follows.

(1) The Hilbert transform of each IMF component is used to obtain an analytic signal.

$$\left(\delta(t)+\frac{\mathrm{j}}{\pi t}\right)\cdot u_k(t) \quad (6)$$

(2) The center frequency is estimated using the obtained analytic signal, and the spectrum of each analytical signal is transformed into a baseband with a frequency shift.

$$\left[\left(\delta(t)+\frac{\mathrm{j}}{\pi t}\right)\cdot u_k(t)\right]\mathrm{e}^{-\mathrm{j}\omega_k t} \quad (7)$$

(3) The L^2 norm of the demodulated signal is calculated, and the bandwidth of each mode is estimated. The variational problem can be expressed as

$$\begin{cases}\min\limits_{\{u_k\},\{w_k\}}\left\{\sum_k\left\|\partial_t\left[\left(\delta(t)+\frac{\mathrm{j}}{\pi t}\right)\cdot u_k(t)\right]\mathrm{e}^{-\mathrm{j}\omega_k t}\right\|^2\right\} \\ \text{s.t.}\sum_k u_k=f(t)\end{cases} \quad (8)$$

(4) For the above mentioned variational problem, the quadratic penalty function and Lagrange multiplier can be used to transform a problem into

an unconstrained problem form.

$$L\left(\{u_k\},\{\omega_k\},\lambda\right)=\alpha\sum_k\left\|\partial_t\left[\left(\delta(t)+\frac{\mathrm{j}}{\pi t}\right)*u_k(t)\right]\mathrm{e}^{-\mathrm{j}\omega_k t}\right\|_2^2+\left\|f(t)-\sum_k u_k(t)\right\|_2^2+\left\langle\lambda(t),f(t)-\sum_k u_k(t)\right\rangle \tag{9}$$

where α is the penalty factor, and $\lambda(t)$ is the Lagrange multiplier.

Finally, a multiplier alternate direction algorithm is used to solve the unconstrained variational problem of Eq.(9), and then the IMF can be obtained.

2 Analysis of Simulation Signal

The anchoring detection signal of an anchor is regarded as a vibration signal. The singular point of the vibration signal is typically used to identify the anchoring quality mark of a bolt. A simulation signal is adopted to verify the ability of the identifying abnormality of the VMD and the study recognition of the VMD and MF-VMD for the vibration signal in an environment with a strong noise.

2.1 VMD decomposition of simulation signal

The simulation signal $s(t)$ has a singular point and two frequencies, namely, 10 and 20 kHz. Fig.1 illustrates the singular points at 0.8 and 1.2 ms.

$$s(t)=\begin{cases}\sin(20\,000\,\pi t) & 0<t\leqslant 0.8\\ \sin(40\,000\,\pi t) & 0.8<t\leqslant 1.2\\ \sin(20\,000\,\pi t) & 1.2<t\leqslant 2\end{cases} \tag{10}$$

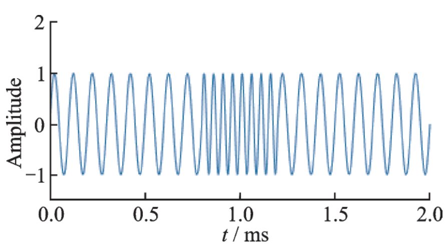

Fig.1 Simulation signal $s(t)$

The simulation test signal $s(t)$ depicted in Fig. 1 is decomposed through the VMD method. Fig.2 displays the decomposition result.

In Fig.2, IMF1 and IMF2 can be completely obtained from signal $s(t)$ and display two types of vibration. Fig. 3 depicts the instantaneous frequency spectrum.

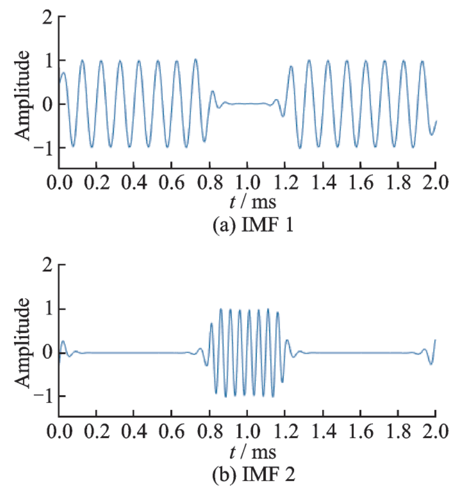

Fig.2 Decomposition of VMD

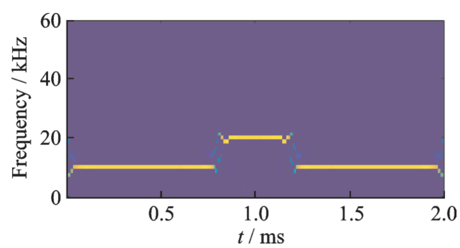

Fig.3 Instantaneous frequency with VMD

Fig.3 demonstrates the two frequencies, namely, 10 and 20 kHz, which appear in the signal. The singularity points are at 0.8 and 1.2 ms. Thus, VMD decomposes the different modes from the signal without noise interferences.

2.2 Simulation signal under noise interferences

The mode selection and spurious level are determined In the studied vibration signal decomposition with VMD, $s(t)$ exhibited in Fig. 1 is added with noise at signal-to-noise ratio (SNR = 5 dB). Fig. 4 presents the simulation signal $s_n(t)$ that contains the noise interference. The VMD is used to decompose $s_n(t)$. Different IMFs can be obtained with VMD. Fig.5 illustrates the results.

In Fig. 5, IMF1 is slightly different from the

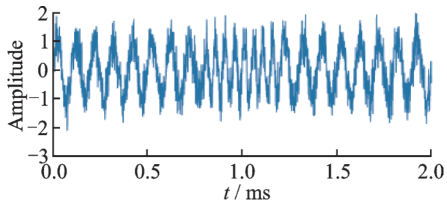

Fig.4 $s_n(t)$ containing noise interference

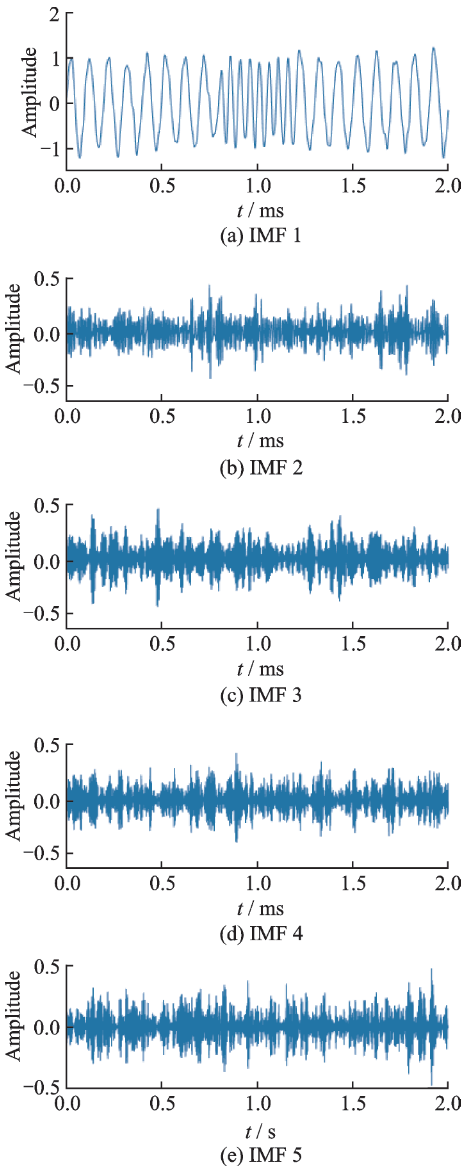

Fig.5 Decomposition results of VMD

original signal, namely, $s(t)$. However, IMFs2-5 are the noises. VMD is unable to decompose the different modes from $s_n(t)$ given the mixing of the two types of mode signals. Fig.6 depicts that the Hilbert instantaneous frequency derived from VMD.

Fig. 6 demonstrates that the instantaneous frequency continues from the VMD method. Considerable singularities are inexistent in the instantaneous

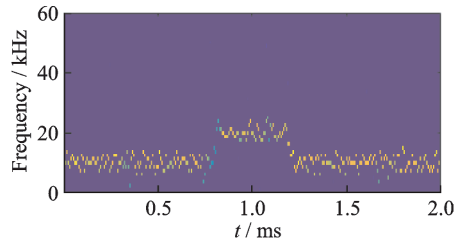

Fig.6 Hilbert instantaneous frequency

frequency. Thus, the vibration signal has an obvious interference.

MF-VMD is also adopted to decompose $s_n(t)$. The IMFs of $s_n(t)$ can be obtained as exhibited in Fig.7.

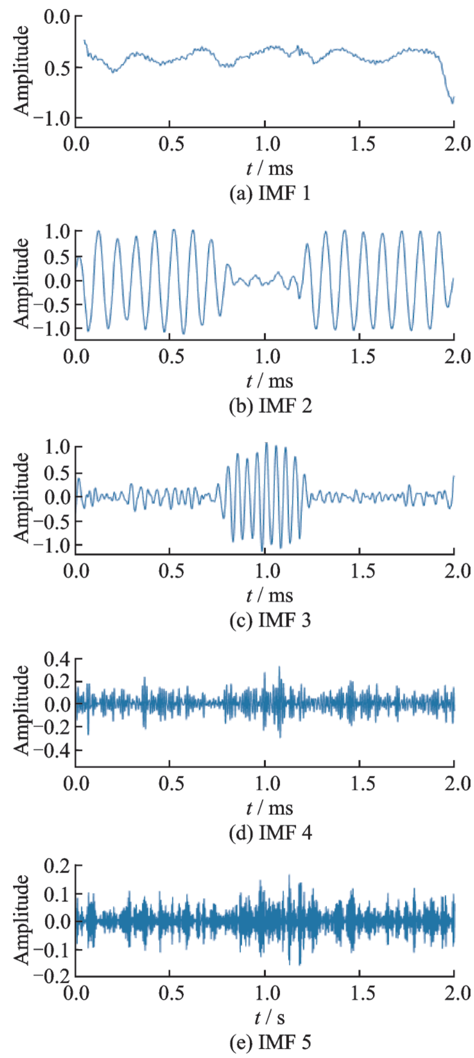

Fig.7 MF-VMD decomposition results

Fig. 7 displays that IMF1, IMF4, and IMF5 are residual noise signals, whereas IMF2 and IMF3 are two modes of $s(t)$ and correspond to IMF1 and IMF2 displayed in Fig.2, respectively. The IMF is adopted from the Hilbert transform. Fig.8 presents

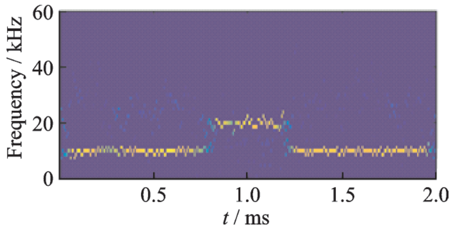

Fig.8 Hilbert instantaneous frequency

the Hilbert instantaneous spectrum.

Fig. 8 illustrates that the spectrum of the instantaneous frequency with the MF-VMD has certain obvious singularities at both frequencies of 10 and 20 kHz. A random interference signal is suppressed well in comparison with the spectrum depicted in Fig. 6. The frequency strength is significantly higher than that demonstrated in Fig. 6. In contrast to a strong noise background, MF-VMD has favorable recognition of singular points of the vibration signals.

3 Bolt Anchoring Detection Signal Analysis

The high-slope bolt anchoring testing site in Yunnan expressway in China is adopted as an example and an AGI-MG bolt quality detector is used as an instrument (Fig. 9). The sampling parameter is 1.05 kHz, the sampling number is 980, and the sampling interval is 4.0 μs. Fig. 10 displays the collected vibration signal 1.


(a) Detection apparatus (b) Testing site

Fig.9 Bolt anchoring testing site

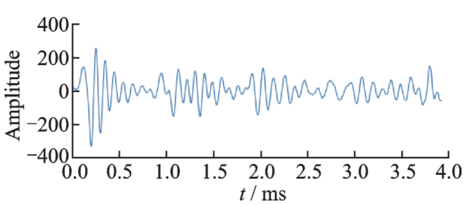

Fig.10 Bolt anchoring detection of signal 1

Directly determining the bottom of the bolt reflection signal presented in Fig. 10 is difficult. Thus, the MF-VMD is adopted to decompose the signal. Fig. 11 illustrates the decomposition result.

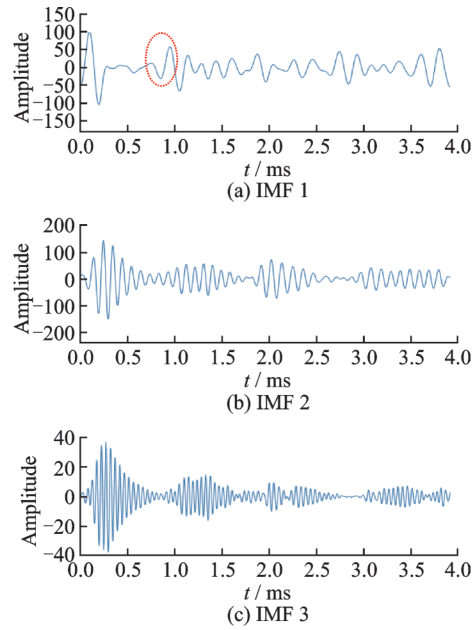

Fig.11 Decomposition of signal 1 with MF-VMD

Fig. 11 demonstrates that three IMFs are obtained through MF-VMD. A reflection signal is observed from the bolt bottom at 1.0 ms in IMF1. Given that the bolt length is 3 m, and the velocity of the wave in the bolt is 6 000 m/s, Reflection signal 2 must be at 1.0 ms.

To further verify the test results, the second testing on the anchor is conducted. Fig. 12 depicts the test result of signal 2.

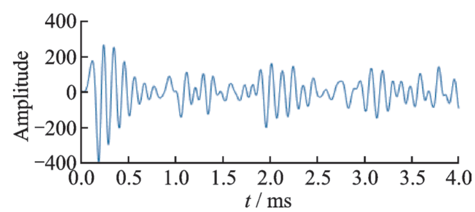

Fig.12 Bolt anchoring detection of signal 2

Fig. 12 denotes that directly judging a low-end reflection signal of the anchor is difficult. Similarly, the proposed MF-VMD method is used to decompose detection signal 2. Fig. 13 exhibits the decomposed result.

Fig. 13 displays that IMF1 shows an obvious

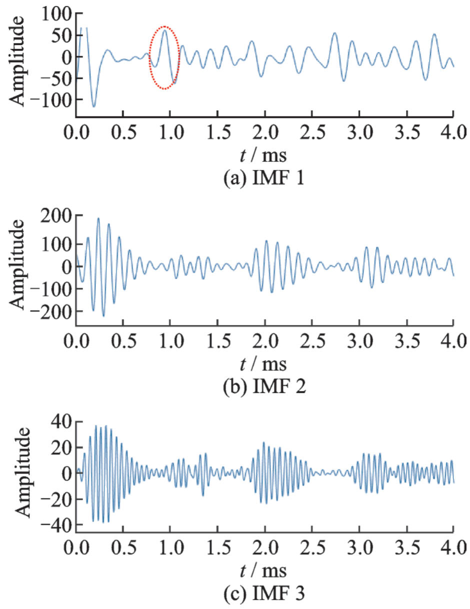

Fig.13 Decomposition of signal 2 with MF-VMD

anchor end reflection time at 1.0 ms, and the reflection time of the bottom end of the anchor is consistent with the IMF1 result presented in Fig. 11. Therefore, the results further verify the applicability of the proposed method. Thus, the proposed method can decompose the reflection signal of the bolt bottom and determine the reflection time.

4 Conclusions

On the basis of VMD principle, VMD theory is introduced into the detection signal analysis of bolt anchoring. With the combination of MF and VMD, the MF-VMD method is proposed to analyze bolt detection signals. On the basis of the analysis of the simulation signal and field application, the following conclusions can be drawn.

(1) VMD can decompose different modes from vibration signals. However, VMD cannot appropriately decompose IMFs from vibration signals with a strong noise interference.

(2) MF-VMD can aptly decompose IMFs from vibration signals even under strong noise interference. Furthermore, this method reduces the effect of noise.

(3) MF-VMD can decompose bolt detection signals into the IMFs, and reflection signals from the bottom of the bolt can also be identified in the IMF.

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Acknowledgements This work was supported by the Key Project of the National Natural Science Foundation of China (No.51739006), the Open Research Fund of the Fundamental Science on Radioactive Geology and Exploration Technology Laboratory (No.RGET1502), the Open Research Fund of Hubei Key Laboratory of Intelligent Vision Based Monitoring for Hydroelectric Engineering (No.2017SDSJ05), and the Project of the Hubei Foundation for Innovative Research Groups (No.2015CFA025).

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Author contributions Dr. **XU Juncai** contributed to implementation of the experiments, analysis of the data and preparing the manuscript. Prof. **REN Qingwen** and Dr. **LEI Bangjun** guided and discussed the study.

Competing interests The authors declare no competing interests.

(Production Editor: Wang Jing)