ISSN: 2710-0588

Damage Identification of Curtain Wall Cables based on Improved VMD and Hilbert Transform

Yujie Liu*

School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai 200093, China

*Corresponding Author

Abstract

Cable is an important role in Curtain wall cable structures. In order to detect cable damage in a timely and accurate manner, this paper focuses on the problem of non-stationary nonlinear vibration information and mode mixing in Empirical Mode Decomposition (EMD) itself. Based on the damage detection method combining Variational Mode Decomposition (VMD) and Hilbert Transform (HT), further parameter optimization is carried out. This method determines the penalty factor and decomposition level K by searching for the minimum envelope entropy. VMD is used to decompose the vibration information into different BIMF components, and then Hilbert transform is applied to the extracted components to obtain the corresponding marginal spectrum. cable damage identification is performed based on the modal anomaly index. This article confirms through local damage analysis of a single cable that this method can effectively identify the damage location and degree of the cable.

Keywords

Cable Damage; Damage Detection; Variational Mode Decomposition; Hilbert Transform; Envelope Entropy.

1. Introduction

Cable-net structure is a kind of structural system in which cables are used as the main stressed members. The cables are tensioned to ensure the stiffness and balance the external load, and part of the external load is transmitted to the main structure through cables. With the wide application and rapid development of cable structure, cable, as an important component of cable net curtain wall structure, inevitably appears different damage situations and problems in engineering application. Rust and breakage of steel wire caused by load, temperature and corrosion, relaxation and creep of cable, damage of anchor end and other factors may be the causes of cable damage. In recent years, accidents caused by local damage of cables have occurred from time to time. For example, cable fracture of Morandi Bridge in Genoa, Italy in 2018 led to collapse of main girder, and suspension cable fracture of Nanfang Bridge in China Taiwan in 2019 led to collapse of whole bridge. Therefore, in order to ensure the safe operation of the whole structure, cable damage identification has become an important research field of cable structure health monitoring and maintenance.

Regarding the current four levels of structural damage identification[1], the commonly used methods for identifying cable damage in recent years include: (1) dynamic fingerprint method based on natural frequency, mode shape (mode), curvature mode, modal strain energy, and frequency response function; (2) Static based damage identification method; (3) A damage identification method based on wavelet analysis. The occurrence of cracks or local damage in the structure can cause changes in the parameters of the structural system itself, namely changes in mass, damping, and stiffness, resulting in a decrease in stiffness, an increase in

ISSN: 2710-0588

damping, and a change in the vibration frequency and mode of the structure[2]. Therefore, when the test data is accurate enough, changes in vibration parameters can be studied to determine and evaluate structural damage. The marginal spectral peak in the Hilbert Huang transform (HHT) method comes from the strain mode and can diagnose the location of structural damage[3]. Changes in the environment and testing conditions affect the changes in modal parameters to varying degrees, and may even mask minor changes caused by structural damage. Due to the mathematical theoretical limitations of Empirical Mode Decomposition (EMD)[4], there may be aliasing of two adjacent IMF waveforms during the decomposition process. However, the filtering, denoising, and modal extraction functions of Variational Mode Decomposition (VMD)[5] can reduce the impact of environmental noise on modal parameter changes, and have good advantages in avoiding modal aliasing problems, making it suitable for nonlinear applications Analysis of non-stationary signals.

In order to solve the problem of damage detection of curtain wall cables, a method based on VMD and Hilbert transform is proposed in this paper. The penalty factor and decomposition layer are further optimized. The Hilbert marginal spectrum is obtained by VMD algorithm, and the damage condition is judged according to the modal anomaly index. Single and multiple local damages of curtain wall cable structure are identified by simulation analysis.

2. VMD-HT Method based on Parameter Optimization

2.1. VMD Algorithm

VMD decomposition is a non-recursive signal processing method. By constructing a variational problem to search iteratively for the optimal solution of the variational mode, time series data can be decomposed into a series of BIMF with finite bandwidth, and the optimal center frequency and bandwidth of each component can be adaptively updated[6].

Suppose that the original signal f is decomposed into k components, the sum of the estimated bandwidths of each component is minimized, and the sum of all modal components is the same as the original signal. The constrained variational model can be expressed as:

$$\min_{\{u_k\},\{\omega_k\}}\left\{\sum_{k=1}^{K}\left\|\partial_t\left\{\left[\left(\delta(t)+\frac{j}{\pi t}\right)\right]*u_k(t)\right\}e^{-j\omega_k t}\right\|_2^2\right\} \tag{1}$$

$$\sum_{k=1}^{K}u_k = f \tag{2}$$

In the formula, $u_k=\{u_1,u_2,\cdots,u_k\}$ represents modal functions; $\omega_k=\{\omega_1,\omega_2,\cdots,\omega_k\}$ represents Center frequencies of each mode.

The above constrained variational problem is transformed into an unconstrained variational problem. In order to make the constraint more strict, quadratic penalty term and Lagrangian multiplier are added, and it is expanded into:

$$L(\{u_k\},\{\omega_k\},\lambda)=\alpha\sum_k\left\|\partial_t[(\delta(t)+\frac{j}{\pi t})*u_k(t)]e^{-j\omega_k t}\right\|_2^2+\left\|x(t)-\sum_k u_k(t)\right\|_2^2+\left\langle\lambda(t),x(t)-\sum_{k=1}^{K}u_k(t)\right\rangle \tag{3}$$

In the formula, α represents penalty factor, λ represents Lagrangian multiplier. In solving equation (3), the proposed unconstrained variational problem adopts the multiplier alternating direction method by alternately updating each eigenmode function u_k, modal center frequency ω_k and Lagrange multiplier λ:

$$\hat{u}_k^{n+1}(\omega) \leftarrow \frac{\hat{f}(\omega) - \sum_{i=1,i<k}^{K} \hat{u}_i^{n+1}(\omega) - \sum_{i=1,i<k}^{K} \hat{u}_i^{n}(\omega) + \frac{\hat{\lambda}^n(\omega)}{2}}{1 + 2\alpha(\omega - \omega_k^n)^2} \tag{4}$$

$$\omega_k^{n+1} \leftarrow \frac{\int_0^\infty \omega \left|\hat{u}_k^{n+1}(\omega)\right|^2 d\omega}{\int_0^\infty \left|\hat{u}_k^{n+1}(\omega)\right|^2 d\omega} \tag{5}$$

$$\hat{\lambda}^{n+1}(\omega) \leftarrow \hat{\lambda}^n(\omega) + \gamma\left[\hat{f}(\omega) - \sum_{k=1}^{K} \hat{u}_k^{n+1}(\omega)\right] \tag{6}$$

In the formula, γ represents noise margin. Continuously update formulas (4-6) alternately until formula (5) is satisfied before stopping the iteration:

$$\sum_{k=1}^{K} (\left\|\hat{u}_k^{n+1} - \hat{u}_k^{n}\right\|_2^2 / \left\|\hat{u}_k^{n}\right\|_2^2) < \varepsilon \tag{7}$$

2.2. Optimize Parameters

Shannon entropy can be used as a criterion to evaluate signal sparsity. The entropy value can reflect the uniformity of probability distribution. The most uncertain probability distribution (equal probability distribution) has the largest entropy value[7]. When there is more noise and less feature information in BIMF, the envelop entropy is larger, otherwise, the envelop entropy is smaller. Therefore, the objective function for optimizing the search is envelope entropy. The envelope entropy H_p of signal $x(i)$（$i = 1,2\cdots,n$) can be expressed as:

$$p_i = a_i / \sum_{i=1}^{n} a_i \tag{8}$$

$$H_p = -\sum_{i=1}^{n} p_i \lg p_i \tag{9}$$

In the formula, $a(i)$ is the envelope signal obtained by Hilbert transform of BIMF component after decomposition of $x(i)$; $p(i)$ is the normalized form of $a(i)$; parameter optimization of VMD decomposition mainly solves the problem of setting penalty factor α and decomposition layer K. If K is too small, it cannot correctly reflect the effective information in the signal, that is, mode loss; if K is too large, it will lead to mode aliasing; improper setting of penalty factor α will also affect mode aliasing and loss.

2.3. Hilbert-Huang Transformation

Hilbert transform is performed on the output BIMF component. Since the original signal x(t) is a function of the instantaneous frequency $\omega_i(t)$ and time t corresponding to the component, the original signal is expressed as:

$$H(\omega, t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t) e^{j\int \omega_i(t) dt} \tag{10}$$

ISSN: 2710-0588

In the formula, Re represents the real part; $a_i(t)$ is the instantaneous amplitude of the signal; $H(\omega, t)$ obtained in this case is the Hilbert spectrum, and integrating it with time results in the marginal spectrum $h(\omega)$:

$$h(\omega)=\int_0^T H(\omega,t)dt \tag{11}$$

The meaning of $h(\omega)$ is expressed as the sum of amplitudes at different times of a certain frequency, that is, the distribution of the amplitude of the vibration signal at different frequencies. Unlike power spectrum, which can only reflect the likelihood of the existence of a certain frequency, marginal spectrum can accurately determine whether a certain frequency actually exists, and its accuracy and resolution are also higher.

2.4. Damage Identification Index

Modal can effectively reflect the structural vibration characteristics, and modal parameters change with structural damage, thus realizing structural damage identification. Because the peak value of marginal spectrum comes from strain mode, the amplitude and frequency of strain mode can be obtained from marginal spectrum. In this paper, damage identification is carried out by comparing the modal component vectors in intact state and damaged state:

$$\xi=\frac{h(\omega_i)}{\sum_{i=1}^{n}h(\omega_i)} \tag{12}$$

In the formula, ξ represents the relative proportion of each frequency component of the signal; the proportion of each modal component changes with the position change, and the amount of change before and after the damage is also different. The damage position is analyzed through the change of the proportion relationship. Further define the anomaly index[8]:

$$D_f=1-\frac{\left|\sum_{i=1}^{n}\xi^u\xi^d\right|^2}{\sum_{i=1}^{n}(\xi^u)^2\sum_{i=1}^{n}(\xi^d)^2} \tag{13}$$

In the formula, ξ^u and ξ^d are modal component vectors for undamaged and damaged modes; By analyzing and comparing the matching degree of each frequency component before and after damage, it is determined whether the distribution of modal components has changed. When $D_f=0$, it indicates that the modal components have not changed, indicating that the structure is undamaged; The larger the value of D_f, the larger the change variable, indicating the occurrence of structural damage.

The flowchart based on the improved VMD-HT algorithm is shown in Figure 1.

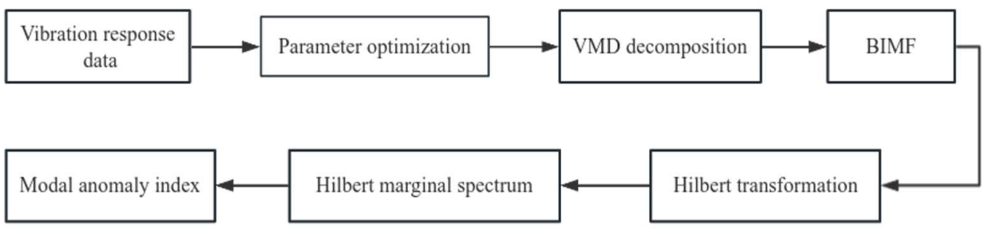

Figure 1. The flow chart of damage identification method based on VMD-HT

ISSN: 2710-0588

3. Numerical Examples

As shown in Figure 2, a curtain wall cable is simplified as a string structure with fixed supports at both ends, and discretized into 10 uniform string elements through finite element analysis. The length of the cable is 10m, with a diameter of 10mm. The initial prestress of the cable is 10kN, and the density is 7800kg/m3.

Figure 2. Cable node distribution

Set an area damage of 15% at the 9th unit between nodes 9 and 10 of the cable, denoted as a single local damage situation, and excite at node 8 with a sampling frequency of 200Hz and a sampling time of 1s. Take the vibration response signal at node 8 before damage as the observation data. The range of parameter decomposition levels K is set to 3 to 9, and the range of penalty factors α is 500 to 4000. The improved VMD algorithm is used to decompose the signal, and the parameters are optimized according to the limit of envelope entropy. As shown in Table 1, the minimum envelope entropy value is 2.139, corresponding to parameters K=7 and α =500.

Table 1. Envelope Entropy of Different Parameters

α	K						
	3	4	5	6	7	8	9
500	2.176	2.186	2.157	2.156	2.139	2.150	2.140
1000	2.176	2.173	2.155	2.165	2.144	2.148	2.148
1500	2.176	2.173	2.185	2.169	2.147	2.162	2.146
2000	2.176	2.189	2.196	2.198	2.188	2.165	2.149
2500	2.176	2.190	2.196	2.191	2.182	2.171	2.156
3000	2.176	2.191	2.196	2.191	2.183	2.171	2.156
3500	2.177	2.192	2.206	2.191	2.184	2.173	2.181
4000	2.177	2.193	2.206	2.199	2.192	2.175	2.173

The VMD algorithm is used to decompose the vibration response signal at node 8 into BIMF components from high frequency to low frequency, and the BIMF components of each order are shown in Figure 3. Then Hilbert transform is used to process the BIMF components of each order, and the corresponding marginal spectrum $h(\omega)$ is obtained as shown in Figure 4. The marginal spectrum amplitude decreases with the damage degree, which proves that the marginal spectrum amplitude is related to the damage degree. According to the amplitude change, the damage degree of the structure can be judged.

ISSN: 2710-0588

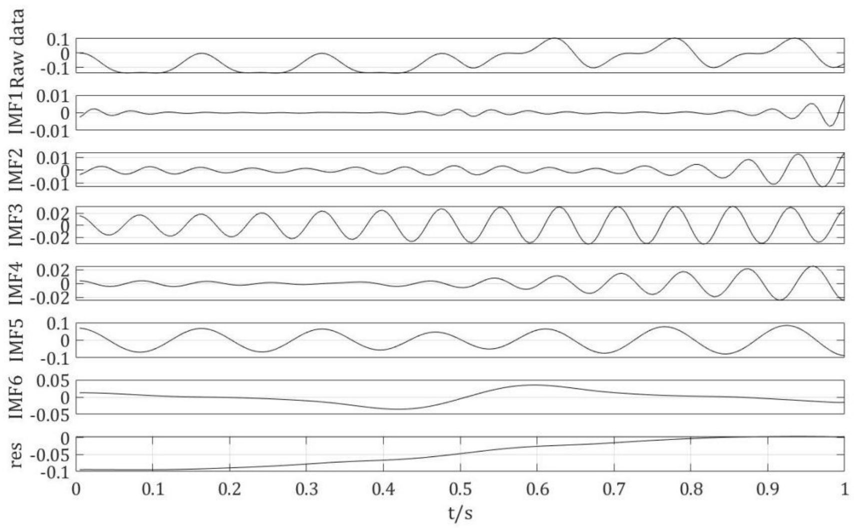

Figure 3. VMD decomposition of intact structure at measurement point 8

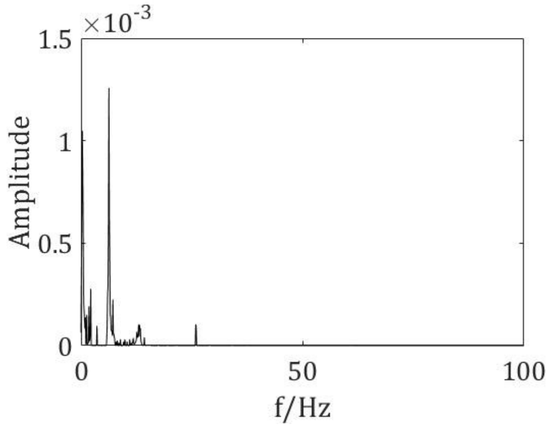

Figure 4. Marginal spectrum at node 8 of intact structure

In order to further identify the location of damage, the modal anomaly index D_f values under different working conditions and different nodes are calculated to further determine the damage location. The modal anomaly index results corresponding to each node are shown in Table 2. The D_f values of node 9 and node 10 are relatively large compared with other nodes, indicating that the damage degree between the two nodes is relatively serious. The damage position is located between nodes 9 and 10. In order to simulate multiple localized damages, area damage of 15% was set at element 4 between nodes 4 and 5, and damage of 10% was set at element 7 between nodes 7 and 8. With the increase of damaged parts, the overall D_f value changes obviously compared with the amplitude of single damage case. The index of nodes 4,5,7,8 is larger than that of other nodes, which is judged as the most serious damage parts of the whole cable. Moreover, the damage degree of nodes 4,5 is deeper than that of nodes 7,8, corresponding to the simulation situation.

Table 2. D_f of each node in local damage

Nodes	2	3	4	5	6	7	8	9	10
Unit 9 damage 15%	0.115	0.119	0.121	0.125	0.131	0.173	0.186	0.249	0.222
Unit 4 damage 15%; unit 7 damage 10%	0.234	0.316	0.478	0.444	0.301	0.347	0.321	0.254	0.241

ISSN: 2710-0588

The results of this example confirm that the damage identification method based on VMD-HT can detect single or multiple local damages in the structure, but this method can only distinguish the location and qualitative degree of structural damage, and further quantitative damage degree still needs to be studied.

4. Conclusion

In this paper, a new method for damage detection of curtain wall cable structure based on variational modal decomposition and Hilbert transform is proposed. Numerical examples show that the proposed method has the following characteristics:

(1) The damage judgment can be made only by detecting the vibration response signal of a certain measuring point and processing the signal accordingly. This method is practical in engineering practice.

(2) In case of local damage, the damage index of adjacent nodes at the damage position will increase correspondingly, and the change of multi-damage position is more obvious. The damage judgment result is consistent with the assumed damage. This method can identify the local damage position and qualitatively damage degree, and provide reference value for cable damage evaluation of cable net curtain wall structure in practical engineering.

(3) Due to the lack of specific engineering case analysis in the article, the accuracy of damage detection results will be affected by different environmental and conditional factors, as well as uncertainties caused by random vibration in actual testing. How to reduce and distinguish the influence of other factors on changes in structural modal parameters urgently needs to be solved.

References

[1] S.W. Doebling, C.R. Farrar, M.B. Prime, et al. Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics:a Literature Review[M]. USA: Los Alamos National Laboratory, 1996: LA-10370-MS.

[2] W. C. Gao, W. Liu, J. X. Zou. Damage detection methods based on changes of vibration parameters:asummary review[J]. Journal of Vibration and Shock, 2004, (04): 3-9+19+146. (In Chinese).

[3] Z. F. Sun, K. Z. Guo, K. Tu . Study of structural damage identification based on improved Hilbert-Huang transform [J]. Engineering Construction, 2019, 51(01): 19-25. (In Chinese).

[4] E. N. Huang, Z. Shen, R. S. Long, et al. The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-Stationary Time Series Analysis[J]. Proceedings: Mathematical, Physical and Engineering Sciences, 1998, 454(1971): 903-995.

[5] Konstantin Dragomiretskiy, Dominique Zosso. Variational Mode Decomposition[J]. IEEE Trans. Signal Processing, 2014, 62(3): 531-544.

[6] X. X. Jiang, Q. Y. Song, G. F. Du, et al. Review on research and application of variational mode decomposition [J]. Chinese Journal of Scientific Instrument, 2023, 44(01): 55-73. (In Chinese).

[7] Z. H. Zhao, S. p. Yang. Roller Bearing Fault Diagnosis Based on Wavelet Packet Transform and Sample Entropy [J]. Vibration. Test & Diagnosis, 2012, 32 (04): 640-644+692. (In Chinese).

[8] C. X. Li, F. Q. Chen. Hilbert-Huang transfrom based approach damage feature extraction and alarming[J]. Journal of Changsha University of Science & Technology(Natural Science), 2007, (03): 29-33. (In Chinese).