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MODAL DAMPING PARAMETER IDENTIFICATION METHOD BASED ON IMPROVED VMD AND ENVELOPE FITTING AND ITS APPLICATION

BIAN Jie[1,2], CHEN Ya-nong[1,2], MEI Qing[1,2], XU You-liang[1,2] & LU Yan-hui[1,2]

[1] AECC Hunan Aviation Powerplant Research Institute, Zhuzhou, 412002, China
[2] AECC Key Laboratory of Aero-engine Vibration Technology, Zhuzhou, 412002, China

Abstract

Aiming at the problems of correct separation of multi-modal signals and accurate identification of modal damping parameters of frequency measurement signals, a method of modal parameter identification based on improved variational mode decomposition (IVMD) and envelope fitting (EF) is proposed. Firstly, particle swarm optimization (PSO) algorithm is used to adaptively determine the VMD input parameters to obtain the IVMD method, and the IVMD method is used to accurately separate the multi-modal components of the signal to be decomposed into single-mode signals. Then, for each single-mode signal, the EF method is used to identify its modal frequency and damping ratio. The results of modal decomposition and modal parameter identification of displacement simulation signal and frequency measurement signal of a guide vane show that the IVMD method can realize the correct decomposition of multi-modal signal. The modal frequency identification error of the IVMD-EF method is less than 0.7%, the modal damping identification error is less than 4.0%, and its modal damping identification error is significantly less than that of the half power bandwidth (HPB) method. The maximum difference between the IVMD-EF method and the HPB method is 79.220%.

Keywords: multi-modal signal; particle swarm optimization; variational mode decomposition; envelope fitting; modal damping identification

1. General Introduction

The vibration and sound radiation of rotating machinery systems such as aero-engines are closely related to the damping performance of structural materials. As an important dynamic performance index, damping parameters have a significant impact on the response of structures in the resonance region [1]. In the early stage of the design of rotating machinery system, due to the lack of engineering test data, the damping parameters often use empirical values, resulting in inaccurate prediction of vibration response and evaluation of noise performance. Therefore, the experimental determination of damping parameters is very important for vibration response calculation and design verification of rotating machinery system. Compared with modal frequency and shape, it is more difficult to accurately determine damping parameters. The uncertainty and instability of damping testing make it more obviously affected by the factors such as test signals and identification methods and so on. Therefore, it is very urgent to explore a reliable and practical damping identification method in the design of the structural vibration and noise reduction.

According to whether the modal damping parameter identification is based on time domain signal or frequency domain signal, modal damping identification methods can be divided into time domain method and frequency domain method. The typical frequency domain method is half power bandwidth method [2]. Chen et al. [3] and Ying et al. [4] analyzed the theoretical error of the half power bandwidth method. The results show that the identification result of the half power bandwidth method is affected by the factors such as the half power point, sampling frequency, frequency resolution, identification damping and window function and so on, and the deviation of the damping identification value from the actual value can be several times or even dozens of times. The typical time-domain method is logarithmic attenuation method [5], which is only suitable for single-mode cases, and it is obviously affected by the noise interference [6]. For the actual multi-mode signal, it is necessary to decompose the multi-mode signal into single-mode signals in order to apply the logarithmic attenuation method for damping identification. For multi-mode signal decomposition, there are many classical decomposition methods, such as empirical mode decomposition (EMD) [7], local mean decomposition (LMD) [8], variational mode decomposition (VMD) [9], etc. The defects of the EMD and LMD methods, such as modal aliasing and endpoint effect, restrict their application [10]. Different from the EMD and LMD methods based on the recursive iteration thought, the VMD method is based on the thought of completely non-recursive variational decomposition. However, the input parameters of the VMD method need to be set artificially, which will affect the modal decomposition effect of the VMD method and make it lack of adaptability [11].

Particle swarm optimization (PSO) algorithm has many outstanding advantages, such as fast convergence speed, easy implementation, and adaptability to dynamic environment. It can effectively solve global optimization problems, and has been successfully applied in function optimization, parameter selection and other practical optimization problems [12]. In order to realize the adaptability of the selection of VMD parameters and improve its modal decomposition effect, the input parameters (quadratic penalty factor α and time delay τ) of the VMD method are optimized by the PSO algorithm to obtain the optimal combination of input parameters. On this basis, the envelope fitting (EF) method of single-mode damping identification based on time-domain signal is studied. The damping identification results of simulated and measured signals show that the proposed method can achieve accurate separation of multi-modal vibration attenuation signals in time domain and accurate identification of modal damping parameters.

2. Improved variational mode decomposition (IVMD) method

2.1 Variational Mode Decomposition (VMD)

VMD is an adaptive signal decomposition method for non-stationary signals. The input signal is constructed by Wiener filter and Hilbert transform. The bandwidth and frequency of the variational problem are updated to solve the variational problem. The input signal can be decomposed into a specified number of modal components. The constrained variational model is shown in equation (1) [13].

$$\begin{aligned} &\min_{\{u_k\}\ \{\omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta_t(t) + \frac{j}{\pi t} \right) \cdot u_k(t) \right] e^{-j\omega_k t} \right\|^2 \right\} \\ &s.t. \sum_k u_k = f \end{aligned} \tag{1}$$

Where: $\{u_k\} = \{u_1, u_2, \cdots, u_k\}$ are the K modal components obtained by decomposition; $\{\omega_k\} = \{\omega_1, \omega_2, \cdots, \omega_k\}$ are the center frequencies of the modal components.

In order to change the constrained variational problem of equation (1) into an unconstrained variational problem and to obtain its optimal solution, the quadratic penalty factor α and Lagrange multiplication operator $\lambda(t)$ are introduced. The extended Lagrangian expression is as follows:

$$\begin{aligned} L(\{u_k\}, \{\omega_k\}, \lambda) = \alpha \sum_k \left\| \partial_t \left[\left(\delta_t(t) + \frac{j}{\pi t} \right) \cdot u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 + \\ \left\| f(t) - \sum_k u_k(t) \right\|_2^2 + \left\langle \lambda(t), f(t) - \sum_k u_k(t) \right\rangle \end{aligned} \tag{2}$$

The alternating multiplier algorithm is used to solve the above-mentioned variational constraint problem, and the optimal solution of the constrained variational problem of equation (2) is obtained by alternately updating the saddle points of the extended Lagrangian expressions u_k^{n+1}, ω_k^{n+1} and λ_k^{n+1}. The specific steps are as follows:

1) Initialize u_k^1, ω_k^1, λ_k^1 and $n = 0$.

2) Update u_k and update ω_k according to the following formula:

$$\hat{u}_k^{n+1}(\omega)=\frac{\hat{f}(\omega)-\sum_{i<k}\hat{u}_i^{n+1}(\omega)-\sum_{i>k}\hat{u}_i^{n}(\omega)+\frac{\hat{\lambda}^n(\omega)}{2}}{1+2\alpha\left(\omega-\omega_k^n\right)^2} \quad (3)$$

$$\omega_k^{n+1}\leftarrow\frac{\int_0^\infty \omega\left|\hat{u}_k^{n+1}(\omega)\right|^2 \mathrm{d}\omega}{\int_0^\infty \left|\hat{u}_k^{n+1}(\omega)\right|^2 \mathrm{d}\omega} \quad (4)$$

3) According to $\lambda^{n+1}=\lambda^n+\tau\left(f-\sum u_k^{n+1}\right)$, Update λ.

4) Repeat steps 2) and 3) to judge whether the given accuracy $e>0$ is satisfied.

2.2 Parameter optimization of VMD based on PSO algorithm

Particle swarm optimization (PSO) is a global optimization algorithm based on the study of foraging behavior of birds and fish. The principle is that each particle continuously updates its own velocity and position through learning to search its individual local extremum and population global extremum [14], that is

$$v_{id}^{k+1}=\omega v_{id}^k+c_1\eta\left(p_{id}-x_{id}^k\right)+c_2\eta\left(p_{id}-x_{id}^k\right) \quad (5)$$

$$x_{id}^{k+1}=x_{id}^k+v_{id}^{k+1} \quad (6)$$

Where, $1\le i\le m$, m is the population number, $1\le d\le D$, D is a spatial dimension; k is the current number of iterations; c_1 expresses one's own experience; c_2 represents the experience of the population; η is a random number between 0 and 1; ω is the inertia weight of velocity update in PSO.

According to the principle of PSO, PSO can find the optimal parameter combination according to the maximum or minimum value of a fitness function. Before VMD decomposition, its parameter combination (K,α,τ) needs to be set based on experience, and PSO can just use a criterion function to optimize the parameter combination, which can effectively avoid mode aliasing and distortion of decomposition results due to improper parameter combination setting [15].

Because the parameters of VMD need to be pre-set by experience before decomposition, this paper uses PSO based on fitness function, which takes the larger difference between the peak frequency and amplitude of each mode decomposed by the VMD method and the corresponding peak frequency and amplitude of each mode in the signal to be decomposed as the fitness function to search the optimal parameter combination in the VMD algorithm, in which the number of mode decomposition is determined by the number of peak frequency in the spectrum of the signal to be decomposed.

Since the input parameters (K,α,τ) of VMD need to be preset by experience before decomposition, this paper takes the larger difference between the peak frequency and amplitude of each mode decomposed by the VMD method and the corresponding mode in the signal to be decomposed as the fitness function, and uses PSO to search the optimal parameter combination (α,τ) in the VMD algorithm, in which the number of mode decomposition is determined by the number of peak frequency in the spectrum of the signal to be decomposed.

The main steps of VMD parameter optimization based on PSO are as follows:

1) All parameters and fitness functions of PSO are determined.

2) The position and velocity of particles in PSO are initialized, and the position of particles is set as VMD parameters (α,τ).

3) VMD is used to decompose all the initial particles in PSO, and the fitness values of all modal components u_i are obtained. The minimum fitness value is calculated as a local minimum $\min H_i$.

4) The size of the local minimum $\min H_i$ is compared, and the local minimum of the individual and the global minimum of the population are updated accordingly.
5) Updates the speed and position of particles.
6) Repeat steps (3) to (5) until the maximum number of iterations, and get the global minimum of the population and the position (α, τ) of the corresponding particles.

3. Improved variational mode decomposition (IVMD) method

According to mechanical vibration knowledge [16], in the case of small damping, the motion equation of single degree of freedom damped vibration system is

$$x = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \varphi) \quad (7)$$

Where, A is the amplitude, ζ is the damping ratio, ω_n is the undamped natural frequency, $\omega_d = \omega_n\sqrt{1-\zeta^2}$ is the damped natural frequency, φ is the initial phase.

The motion represented by equation (7) is attenuated vibration, as shown in Figure 1, and its envelope equation is

$$x = \pm Ae^{-\zeta\omega_n t} \quad (8)$$

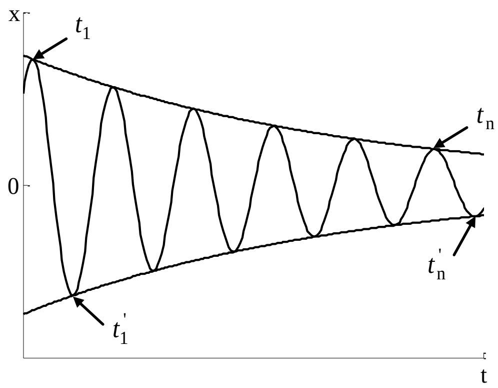


Figure 1 – Time domain waveform and its envelope of a single degree of freedom vibration attenuation signal

In engineering, the free vibration attenuation system is a damped system, so the measured natural frequency is damped natural frequency ω_d. Then equation (8) can be changed to

$$x = \pm Ae^{-\frac{\zeta\omega_d}{\sqrt{1-\zeta^2}}t} = \pm Ae^{-\frac{\delta\omega_d}{2\pi}t} \quad (9)$$

Where, $\delta = 2\pi\zeta / \sqrt{1-\zeta^2}$ is the natural logarithm of the ratio of the amplitudes of any two adjacent vibrations, which is called logarithmic attenuation rate.

The exponential function fitting coefficient B is obtained by fitting the envelope of the measured free vibration attenuation waveform of the single degree of freedom system with exponential function (taking the upper envelope as an example). The logarithmic attenuation rate δ can be obtained by combining formula (9) with the damped natural frequency ω_d obtained by Fourier transform of the free vibration attenuation waveform of the single degree of freedom system.

Then the damping ratio ζ can be calculated by equation (10).

$$\zeta = \sqrt{\frac{\delta^2}{\delta^2 + 4\pi^2}} \quad (10)$$

4. Simulation signal damping identification verification

For a multi-degree of freedom mechanical system, the displacement response under impulse excitation can be expressed as the superposition of displacement responses of multiple single degree of freedom systems [17]. According to the research, the displacement response of mechanical system is generally dominated by low order modes [8]. Therefore, the displacement simulation signal is constructed as follows:

$$\begin{aligned} x(t) &= x_1(t) + x_2(t) + x_3(t) \\ x_1(t) &= 1.2e^{-0.005\times4000t}\sin\left(4000\sqrt{1-0.005^2}t + \pi/2\right) \\ x_2(t) &= 1.0e^{-0.01\times1500t}\sin\left(1500\sqrt{1-0.01^2}t + \pi/3\right) \\ x_3(t) &= 2.0e^{-0.05\times500t}\sin\left(500\sqrt{1-0.05^2}t + \pi/5\right) \end{aligned} \tag{11}$$

The number of analysis points is 1024, and the sampling frequency is 2048Hz. The time domain waveform and its amplitude spectrum are shown in Figure 2. There are three frequency components in the amplitude spectrum of Figure 2, which correspond to $x_1(t) \sim x_3(t)$. If each mode can be separated, the natural frequency and damping ratio of each mode can be further identified.

The IVMD method is used to decompose the displacement simulation signal. In the process of optimizing the input parameters of VMD by PSO algorithm, the larger difference between the peak frequency and amplitude of each mode changes with the number of iterations, as shown in Figure 3. When the number of iterations is 5, the larger difference between the peak frequency and amplitude of each mode changes from 6.205×10^{-4} to 6.185×10^{-4}, and the corresponding input parameters (K, α, τ) of VMD are (3, 592, 0.0663).

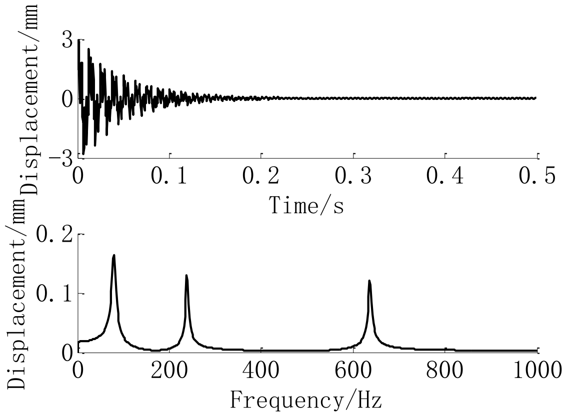


Figure 2 –Time domain waveform and its amplitude spectrum of a displacement simulation signal

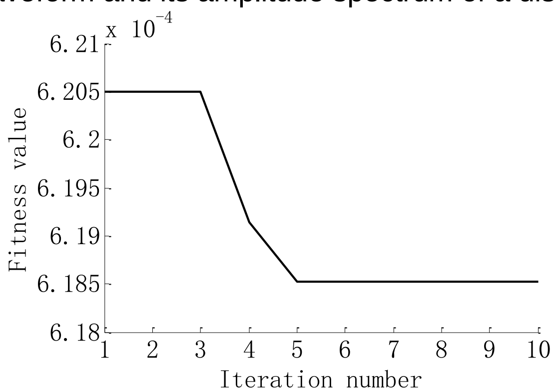


Figure 3 –The larger difference between the peak frequency and amplitude of the displacement simulation signal changing with the number of iterations in the process of IVMD

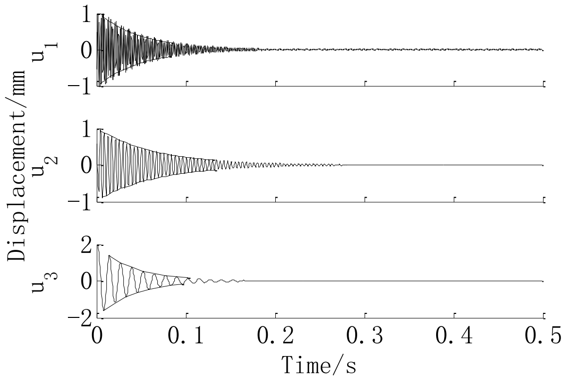


Figure 4 –Time domain waveform and its envelope of each modal component of the displacement simulation signal obtained through IVMD-EF method

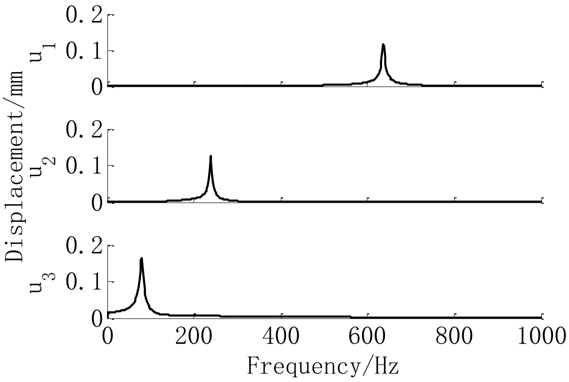


Figure 5 –Amplitude spectrum of each modal component of the displacement simulation signal obtained through IVMD

The decomposition result of displacement simulation signal using the IVMD method is shown in Figure 4. Figure 4 shows that the IVMD method completely separates the three modal components in the displacement simulation signal. Figure 4 shows the envelope lines of the three modal components obtained by the EF method, in which the starting point of the envelope line is the maximum peak or maximum trough, and the ending point is the amplitude of 15% of the maximum peak or minimum trough (the number of peaks and troughs contained in the upper and lower envelope lines is the same), the same below. The fitting equation of the EF method in Figure 4 is completely based on the exponential form of equation (13). Therefore, the extremum of the time domain attenuation signal in Figure 4 is not completely on the envelope. Figure 5 shows the amplitude spectrum of the three modes decomposed by the IVMD method. It is obvious from the spectrum that the u_1~u_3 modal components correspond to the three frequency components from high frequency to low frequency in Figure 2 spectrum.

Table 1 shows the comparison between the circular frequency and damping ratio identified by the IVMD-EF method and the theoretical value. It can be seen from table 1 that the errors between the three modal frequencies identified by the IVMD-EF method and the theoretical values are small, and the maximum error is less than 0.7%, which appears in the x_3 modal component. For the identification of damping ratio, the minimum identification error of the IVMD-EF method is 1.821% in x_3 modal component, and the maximum identification error is 3.961% in x_1 modal component. The damping ratio identified by the IVMD-EF method has little difference from the theoretical value, and the identification errors are relatively small. As a contrast, when the HPB method is used to calculate the three modal damping ratios, the errors are significantly greater than those of the IVMD-EF method, and the maximum error occurs in x_1 modal component, which is 41.066%.

Table 1 –Comparison of the identification results of circular frequency and damping ratio through the IVMD-EF method with their theoretical values

	x_1	x_2	x_3
ω_n (theoretical value)/ (rad/s)	4000.000	1500.000	500.000

ω_n (IVMD-EF)/ rad/s	3996.160	1495.478	503.262
Error between IVMD-EF and theoretical value (ω_n)/ %	0.096	0.301	0.652
ζ (theoretical value)	0.005	0.010	0.050
ζ (IVMD-EF)	0.005198	0.010331	0.049090
Error between IVMD-EF and theoretical value (ζ)/ %	3.961	3.309	1.821
ζ (half power bandwidth method, HPB)	0.002947	0.009617	0.049247
Error between HPB and theoretical value (ζ)/ %	41.066	3.828	1.505

5. Application of modal damping identification of guide vane of compressor

As shown in Figure 6, the guide vane and the outer casing of the compressor are fixed together, and there is a gap between the guide vane and the inner casing (normally, the gap is filled with rubber damping material). The static frequency test of the guide vane in cantilever state is carried out, and the test frequency range is 0~10000Hz. The PCB 352B10 acceleration sensor is placed near the blade root of the back exhaust edge of the measured guide vane, and a small steel bar is used to knock the middle of the back exhaust edge of the guide vane. The guide vane vibrates under the pulse excitation force. The vibration response signal measured by the acceleration sensor is connected to the data acquisition and spectrum analysis system for FFT analysis, and the spectrum diagram is obtained. The static frequency value of the guide vane in the test frequency range can be obtained by reading the frequency value of each spectrum peak on the spectrum. The HPB method can be used to calculate the damping ratio of the guide vane in a certain mode from the peaks in the spectrum. The collected frequency measurement signal and amplitude spectrum of the guide vane are shown in Figure 7. From the amplitude spectrum, it can be seen that there are three-order modes in the frequency range of 0~10000Hz, and the modal frequencies are 6068.12Hz, 2702.64Hz and 863.04Hz, respectively.

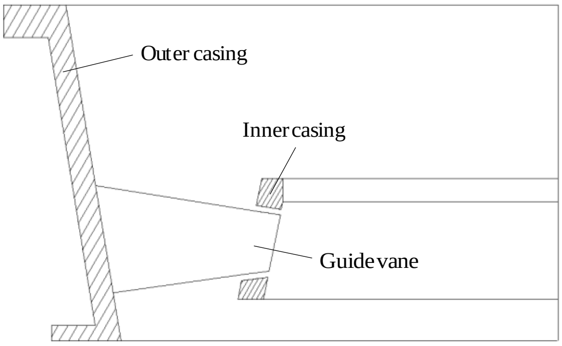


Figure 6 –The schematic diagram of compressor guide vane

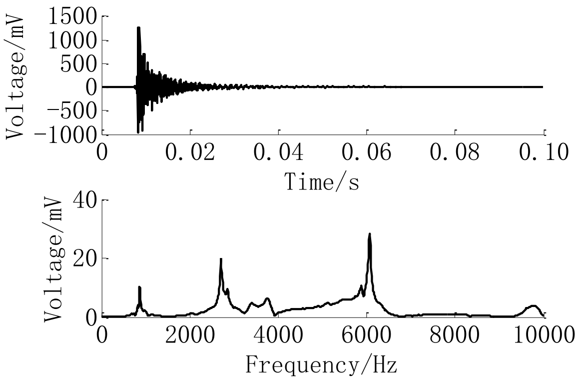
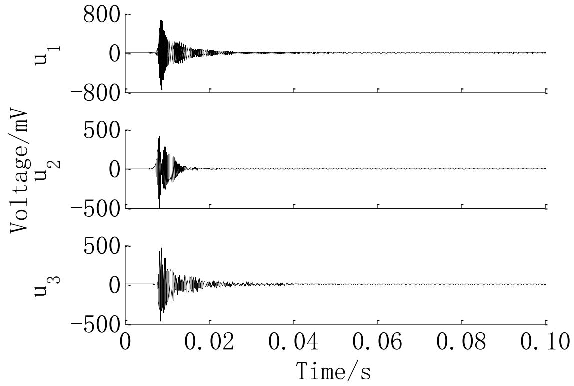
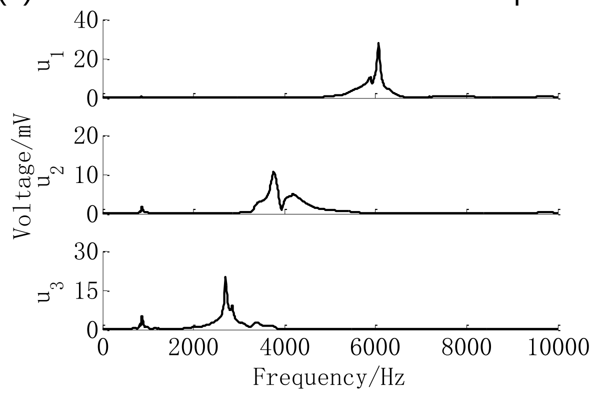


Figure 7 –Time domain waveform and its amplitude spectrum of the frequency measurement signal of a compressor guide vane

In order to verify that the IVMD method has obvious advantages over the VMD method in decomposing the actual signal, the VMD method and the IVMD method are used to decompose the frequency measurement signal of the guide vane respectively. The decomposition of frequency measurement signal by VMD method is shown in Figure 8. It can be seen from Figure 8 that the frequency measurement signal of the guide vane is decomposed into three modal components by VMD method. The time domain waveform is shown in Figure 8(a), and the corresponding frequency spectrum is shown in Figure 8(b). The frequency of u_1 modal component is 6064.45Hz, the frequency of u_2 modal component is 3759.77Hz, and the frequency of u_3 modal component is 2705.08Hz. Therefore, it can be found that the VMD method does not effectively decompose the frequency measurement signal of the guide vane, and the three modal components decomposed by the VMD method have the phenomenon of modal aliasing, so the decomposition fails.



(a) Time domain waveform of each component



(b) Amplitude spectrum of each component

Figure 8 –Time domain waveform and its amplitude spectrum of each component obtained through VMD

In the process of decomposing the frequency measurement signal of the guide vane by the IVMD method, the input parameters of the VMD method are optimized by the PSO algorithm. The convergence curve of the larger difference between the peak frequency and amplitude of each mode with the number of iterations is shown in Figure 9. In the fifth iteration, the larger difference between the peak frequency and amplitude of each mode changes from 6.632×10^{-4} to 6.587×10^{-4}, so the input parameter of the VMD method is (3, 669, 0.0285).

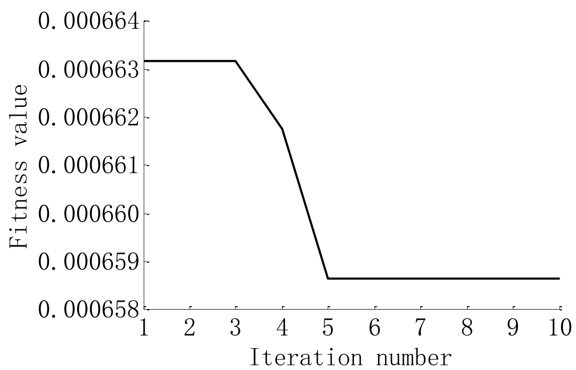


Figure 9 –The larger difference between the peak frequency and amplitude of the frequency measurement signal of the compressor guide vane changing with the number of iterations in the

process of IVMD

Figure 10 shows the decomposition result of the frequency measurement signal of the guide vane using the IVMD method. The time domain waveforms and their envelopes of the three modal components obtained by the EF method are shown in Figure 10. In Figure 10, the time-domain waveform envelope of each modal component obtained by the EF method strictly follows the form of exponential function and does not pass through all extreme points.

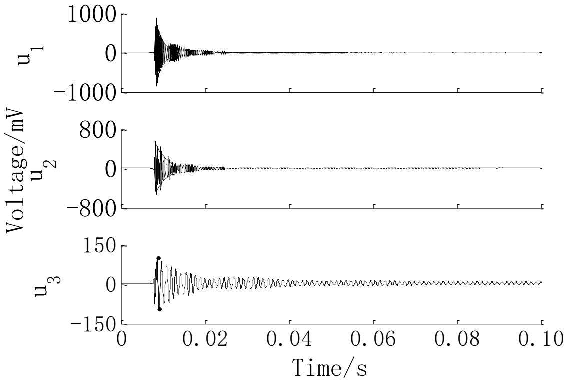


Figure 10 –Time domain waveform and its envelope of each component obtained through IVMD- EF method

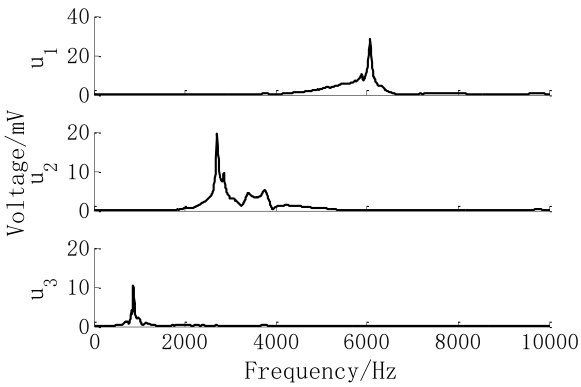


Figure 11 –Amplitude spectrum of each component obtained through IVMD

Figure 11 shows the spectrum of three modal components obtained by the IVMD method. As it can be seen from Figure 11, the frequencies of u_1, u_2 and u_3 modal components are 6064.45Hz, 2705.08Hz and 859.38Hz respectively, which correspond to the three modal frequencies in the spectrum diagram of the guide vane in Figure 7. Therefore, it is proved that the IVMD method can realize the correct decomposition of the guide vane modal components.

Table 2 shows the comparison of frequency and damping ratio identification results obtained by IVMD-EF method with test results and HPB method. As a classical method to identify damping ratio, HPB method has a long history in modal damping identification. Although the HPB method has a large error in identifying the damping ratio [18,19], because the damping ratio of the guide vane is unknown, this paper still takes the damping results identified by HPB method as a reference, and makes a comparative analysis with the damping ratio identified by IVMD-EF method.

Table 2 –Comparison of frequency and damping ratio identification results through the IVMD-EF method with the measurement frequencies and HPB identified results

	3rd order (u_1)	2nd order (u_2)	1st order (u_3)
f (measured value)/ Hz	6068.12	2702.64	863.04
f (IVMD-EF)/ Hz	6064.45	2705.08	859.38
Error between IVMD-EF and measurement (f)/ %	0.060	0.090	0.425
ζ (HPB)	0.005025	0.008194	0.014491
ζ (IVMD-EF)	0.014804	0.023081	0.069734

Difference between IVMD-EF and HPB (ζ)/ %	66.055	64.501	79.220

It can be seen from table 2 that for the identification of the first three-order modal frequencies of the guide vane, the error of the first three-order modal frequencies identified by the IVMD-EF method is close to the test value, and the maximum error of the identification frequency and the test value appears in the first order, with the error less than 0.5%. It is proved that the IVMD-EF method can effectively identify the first three-order modal frequencies of the guide vane.

In the identification of damping ratio, the maximum difference between the IVMD-EF method and the HPB method is 79.220%, which appears in the first mode. Combined with the conclusion that the accuracy of HPB method in modal damping ratio identification is not as good as the IVMD-EF method in the simulation calculation in Section 4, it can be considered that the IVMD-EF method and the HPB method are quite different in modal damping ratio identification of the guide vane, which shows that the IVMD-EF method has advantages over the HPB method in modal damping identification accuracy of real vanes.

6. Conclusion

In this paper, an IVMD method is proposed to separate multi-modal vibration attenuation signals in time domain. On this basis, an envelope fitting (EF) method for modal damping identification is proposed. The main conclusions are as follows:

(1) Compared with the VMD method, the IVMD method can separate the modal components of multi-modal time-domain vibration attenuation signal more accurately without modal aliasing.

(2) The simulation results show that for the identification of modal frequency, the error between the identification value of the IVMD-EF method and the theoretical value is relatively small, and the maximum error is less than 0.7%; For the identification of modal damping, the error between the identification value of the IVMD-EF method and the theoretical value is small (less than 4.0%). When calculating the three modal damping ratios, the error between the HPB method and the theoretical value is significantly larger than that of the IVMD-EF method, and the maximum error is 41.066%.

(3) The modal parameter identification of a compressor guide vane shows that for the modal frequency identification, the error between the frequency identified by the IVMD-EF method and the measured value is less than 0.5%. For modal damping identification, the maximum difference between the IVMD-EF method and the HPB method is 79.220%. The IVMD-EF method is superior to the HPB method in the modal damping identification accuracy.

7. Contact Author Email Address

The contact author email address: bianjie_hrbeu@163.com.

8. Copyright Statement

References

[1] Tang Y H, Wang X R and Li X. Variable frequency excitation response analysis and inverse theory research of modal damping. *Journal of Ship Mechanics,* Vol. 23, No. 11, pp 1339-1350, 2019.

[2] Li H, Sun W, Liu Y, et al. Damping identification for stiffness-nonlinearity structures. *Journal of Vibration and Shock*, Vol. 34, No. 9, pp 131-135,176, 2015.

[3] Chen K F, Jiao Q Y. Influence of linear interpolation approximation to half power points on the damping estimation precision. *Journal of Mechanical Strength*, Vol. 24, No. 4, pp 510-514, 2002.

[4] Ying H Q, Liu J M and Shen S. Half-power bandwidth method and INV damping ration solver study. *Noise and Vibration Control*, Vol. 26, No. 2, pp 4-6, 2006.

[5] Yao L, Zhang K Y, Du M, et al. Research on time domain identification technology of structural modal damping and its application. *Engineering and Construction*, Vol. 32, No. 5, pp 656-660, 2018.

[6] Qin S Q, Kang J T and Kong F. Study on the discreteness of damping ratio identified from operational modal analysis of bridge structure. *Journal of Vibration, Measurement & Diagnosis*, Vol. 36, No. 1, pp 42-48, 2016.

[7] Shen G H, Xiang G T and Xing Y L, et al. Identification of damping characteristics of transmission towers using EEMD. *Journal of Vibration and Shock*, Vol. 33, No. 21, pp 38-43, 2014.

[8] Cheng J S, Zhu W F and Li B Q. Method of identifying analog parameters based on LMD. *Computer Engineering and Applications*, Vol. 51, No. 14, pp 214-218, 2015.

[9] Dragomiretskiy K, Zosso D. Variational Mode Decomposition. *IEEE Transactions on Signal Processing*, Vol. 62, No. 3, pp 531-544, 2014.

[10] Yin H, Dong K L and Peng Z R. Structural modal parameter identification based on VMD-SSI. *Journal of Vibration and Shock*, Vol. 39, No. 10, pp 81-91, 2020.

[11] Wu S Z, Bian J and Chen Y N, et al. Method of modal separation and damping parameter identification of each mode of multi-modal vibration attenuation signals in time domain. *Journal of Propulsion Technology*, Vol. 40, No. 8, pp 1861-1868, 2019.

[12] Shi Z B, Chen C H and Cao L H. Study of diagnosis of any fault occurred to the rotor of a steam turbine based on the cloud particle swarm optimization-supporting vector machine (CPSO-SVM). *Journal of Engineering for Thermal Energy and Power*, Vol. 33, No. 6, pp 41-47, 2018.

[13] Xu T, Wang H J and Song Z Y, et al. Rolling bearing fault diagnosis using VMD energy feature and PNN based on Kullback-Leibler divergence. *Journal of Electronic Measurement and Instrumentation*, Vol. 33, No. 8, pp 117-123, 2019.

[14] Wei Y H, Cao H and Lu Z Q. Application of variational mode decomposition and particle swarm optimization support vector machine method in fault diagnosis of rotor rubbing. *Journal of Shenyang Ligong University*, Vol. 38, No. 4, pp 45-51, 2019.

[15] Jiang L Y, Lu X D and Wang J L, et al. Feature parameters extraction method of gear based on PSO-VMD. Manufacturing Technology & Machine Tool, No. 11, pp 65-71, 2017.

[16] Ji W M, Fang T and Chen S Q. *Mechanical Vibrations*. 1st edition, P.R.C. Science Press, 1985.

[17] Bian J, Huo C Q and Wang P, et al. Application of IITD algorithm in the modal parameter identification of a lubricant oil pipe. *Journal of Zhengzhou University (Engineering Science)*, Vol. 39, No. 1, pp 84-89, 2018.

[18] Zheng L X, Liu G Q and Mei Q, et al. Research of measuring rotating mechanical modal damping by phase matching method. *Journal of Vibration, Measurement & Diagnosis*, Vol. 34, No. 2, pp 218-222, 2014.

[19] Bian J. Damping Determination of Rotating Blades Based on Tip-Timing and Phase Tangent. *Journal of Propulsion Technology*, Vol. 38, No. 8, pp 1840-1846, 2017.