文章编号:0253-2778(2020)03-0271-11

LMD-BPF method for modal parameter identification and its applications

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Abstract: In view of the difficulties existing in the accurate identification of structures' modal parameters, a modal parameter identification method based on local mean decomposition (LMD) and band-pass filtering (BPF) was proposed. Firstly, the LMD method was used in the decomposition of a displacement simulation signal and a frequency measuring signal of a compressor guide vane, and modal aliasing phenomenon existed in the decomposed PF components; Then, the LMD-BPF method was utilized in the decomposition of the displacement simulation signal and frequency testing signal of the guide vane, and each modal frequency was accurately and successfully separated; Finally, the LMD-BPF modal parameter identification method was employed to identify the modal parameters of the displacement simulation signal and frequency testing signal of the guide vane. The maximum errors between the four modal frequencies and damping ratios of the identified displacement simulation signal and the corresponding theoretical values were 0.205% and 2.387%, respectively. The maximum difference between the three modal frequencies of the identified guide vane and the testing frequencies was less than 1.0%, and the maximum difference between the three modal damping ratios of the identified guide vane and those identified by half power bandwidth method was less than 0.65%. The simulation analysis and experimental study of modal parameter identification verified the validity of the proposed method.

Key words: modal parameter identification; local mean decomposition; band-pass filtering; compressor guide vane

CLC number: O157.4　　**Document code**: A　　doi:10.3969/j.issn.0253-2778.2020.03.003

2010 Mathematics Subject Classification: 94B15

Citation: BIAN Jie, ZHENG Jinni, CHEN Yanong, et al. LMD-BPF method for modal parameter identification and its applications[J]. Journal of University of Science and Technology of China, 2020, 50(3): 271-281.

边杰,郑锦妮,陈亚农,等. 模态参数识别的LMD-BPF方法及其应用[J]. 中国科学技术大学学报, 2020,50(3):271-281.

模态参数识别的LMD-BPF方法及其应用

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摘要:鉴于准确识别结构模态参数存在的问题,提出了一种局部均值分解(LMD)-带通滤波(BPF)的模态参

Received: 2018-12-24; **Revised**: 2019-05-31

Foundation item: Supported by Aeronautical Science(2014ZD08007).

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数识别方法。首先，将 LMD 方法用于位移仿真信号和压气机导向叶片测频信号的分解，分解得到的 PF 分量存在模态混叠现象；然后，使用 LMD-BPF 方法对位移仿真信号和导向叶片测频信号进行分解，成功实现了对各模态频率的准确分离；最后，使用 LMD-BPF 模态参数识别方法对位移仿真信号和导向叶片测频信号进行模态参数识别。识别的位移仿真信号 4 个模态频率和阻尼比与相应的理论值之间的最大误差分别为 0.205％和 2.387％，识别导向叶片的 3 种模态频率与测试模态频率之间的最大差别小于 1.0％，识别的导向叶片的 3 种模态阻尼比与半功率带宽法识别的阻尼比，最大差别小于 0.65％。模态参数识别的仿真分析和实验研究验证了该方法的有效性。

关键词：模态参数识别；局部均值分解；带通滤波；压气机导向叶片

0 Introduction

As two important modal parameters, modal natural frequency and damping ratio can provide a valuable reference for the structural design and optimization, simulation calculation and analysis, load identification and application, fault detection and diagnosis etc.. Therefore, structural modal parameter identification is of great significance in the field of mechanical vibration. Due to the difficulties in identification and poor measurement repeatability, the identification of modal parameters, especially damping ratio, has been a hot spot for researchers.

The modal parameter identification method can be divided into time domain method, frequency domain method and time-frequency method. The most representative time domain method is the logarithmic decrement method[1]. The time domain method usually can only process stationary signals, and it is more sensitive to the interference of noise, and it is not suitable for the multi-modal identification problems. The most commonly used frequency domain method is half power bandwidth method[2]. The frequency domain method is based on Fourier transform and capable of identifying multi-modal parameters. However, it can be influenced by factors such as sampling frequency, frequency resolution and analysis points. The actual vibration signals in engineering are generally nonlinear and non-stationary signals, and neither the time domain method nor the frequency domain method can deal with nonlinear and non-stationary signals. In order to deal with nonlinear and non-stationary signals, time-frequency method needs to be adapted. Time-frequency method is a new modal parameter identification method. The typical time-frequency method involves short time Fourier transform (STFT)[3], the wavelet transform (WT)[4], and empirical mode decomposition (EMD)[5] and local mean decomposition (LMD)[6] etc..

STFT is also called the window Fourier transform, and it has fixed time window width, which makes the time-frequency resolution constant. In other words, the frequency resolution and time resolution of STFT influence each other. If the frequency resolution is high, then the time resolution is low, and vice versa[7]. WT lacks adaptability in the localization of signals, and the selection of wavelet base in the transform has a great influence on the analysis results[8]. EMD can adaptively decompose signals, but it has problems such as over envelope, under envelope, modal aliasing and endpoint effect[9-10]. LMD is another adaptive time-frequency analysis method, and it is better than EMD in suppressing the modal aliasing and endpoint effect[11-12]. Meanwhile, it also has fast computing speed, and the calculated instantaneous frequency is always positive[13]. However, LMD itself has the modal aliasing phenomenon[14], and it is also affected by factors such as measurement noise which may cause problems such as decomposition failure[15].

An LMD-BPF modal parameter identification method is proposed in the paper. The method is used in the modal component separation and in the modal parameter identification of a displacement simulation signal and a frequency testing signal of a compressor guide vane, which is to verify the effectiveness of the method in correctly separating modal components and in accurately acquiring modal parameters.

1 Modal parameter identification based on LMD-BPF method

1.1 Fundamental principle of LMD

The essence of local mean decomposition (LMD) is to extract a set of pure frequency modulation signals and envelope signals from the original signal, and a series of PF components can be obtained by multiplying the two together. The decomposition process of LMD involves a triple circulation. For any signal, the specific decomposition process is as follows:

(I) Find out all the local extremum points n_i of the original signal $x(t)$, and calculate the average values m_i of all adjacent local extremum points. Local mean functions $m_{11}(t)$ can be obtained by smoothing processing using the moving average method.

$$m_i = (n_i + n_{i+1})/2 \tag{1}$$

(II) Calculate the envelope estimate value a_i, and the envelope estimation function $a_{11}(t)$ is obtained by smoothing processing in the same smoothing way.

$$a_i = |n_i - n_{i+1}|/2 \tag{2}$$

(III) Extract local mean function $h_{11}(t)$ from the original signal $x(t)$, and it is divided by envelope estimate function $a_{11}(t)$ for demodulation, then there is

$$s_{11}(t) = h_{11}(t)/a_{11}(t) \tag{3}$$

To repeat the above steps for $s_{11}(t)$, and the envelope estimation $a_{12}(t)$ of the $s_{11}(t)$ is obtained. If $a_{12}(t)$ is not equal to 1, repeat the above iterative process until $s_{1n}(t)$ is a pure frequency modulation signal.

(IV) Multiply all the envelope estimate functions generated in the iterative process to gain instantaneous amplitude function $a_1(t)$ (envelope signal):

$$a_1(t) = a_{11}(t)a_{12}(t)\cdots a_{1n}(t) \tag{4}$$

(V) Multiply the envelope signal $a_1(t)$ and the pure frequency modulation signal $s_{1n}(t)$ together to get the first PF component:

$$\mathrm{PF}_1(t) = a_1(t)s_{1n}(t) \tag{5}$$

It contains the highest frequency components of the original signal and it is a single-component AM-FM signal. Its instantaneous amplitude is just envelope signal, and its instantaneous phase can be given by the pure frequency modulation signal, that is

$$\theta_1(t) = \arccos(s_{1n}(t)) \tag{6}$$

(VI) Extract the first PF component $\mathrm{PF}_1(t)$ from the original signal $x(t)$ to obtain $u_1(t)$. Taking $u_1(t)$ as the original signal, repeat the above steps k times until $u_k(t)$ is a monotonic function. At this point, the original signal $x(t)$ is decomposed into the sum of k PF components and a monotonic function $u_k(t)$, then there is

$$x(t) = \sum_{p=1}^{k} \mathrm{PF}_p(t) + u_k(t) \tag{7}$$

Construct an analytical signal $z_p(t)$ through $\mathrm{PF}_p(t)$ and its Hilbert transform $H[\mathrm{PF}_p(t)]$.

$$z_p(t) = \mathrm{PF}_p(t) + iH[\mathrm{PF}_p(t)] = a_p(t)e^{i\theta_p(t)} \tag{8}$$

1.2 LMD-BPF Method

Just like the EMD method, LMD can decompose an original signal into a set of modal components with frequencies from high frequency to low frequency. Actually, similar to the EMD, for some signals such as free attenuation vibration signals, LMD has a serious modal aliasing phenomenon, and it cannot extract each modal component, thus affecting the effective identification for each modal parameter. Aiming at this problem, a method named LMD-BPF method was proposed to realize the effective separation of different modal components by adopting a band-pass filter (BPF) to improve the LMD decomposition process. The concrete implementation process of LMD-BPF is as follows:

In Step (V) of the LMD decomposition, the first PF component is obtained. As there exists modal aliasing phenomenon, the obtained PF component is not strictly a PF component, and it can be denominated as a pre-PF component. Therefore, after the Step (V), the modal aliasing of the PF component needs to be checked. Firstly, amplitude spectrum pre-$PF_1(\omega)$ of the pre-$PF_1(t)$ is gained through the fast Fourier transform. If pre-$PF_1(\omega)$ has q ($q \geqslant 1$) resonant peaks and $q > 1$, then the average frequency $f_{1,\mathrm{BPF}}(\omega) = (f_{1,q}(\omega) + f_{1,q-1}(\omega))/2$ of the qth frequency $f_{1,q}(\omega)$ and the $(q-1)$th frequency $f_{1,q-1}(\omega)$ is calculated, and the frequency $f_{1,\mathrm{BPF}}(\omega)$ is regarded as the high pass cut-off frequency of the bandpass filter. Then, the time domain signal $PF_1(t)$ is obtained through inverse fast Fourier transform of the frequency domain signal $PF_1(\omega)$ after band pass filtering. The pre-$u_1(t)$ is then obtained by subtracting $PF_1(t)$ from $x(t)$ and pre-$u_1(\omega)$ is gained after the Fourier transform of the pre-$u_1(t)$. Furthermore, $u_1(\omega)$ is acquired through bandpass filtering of the pre-$u_1(\omega)$, and $u_1(t)$ is obtained by inverse fast Fourier transform of the $u_1(\omega)$. Meanwhile, the $u_1(t)$ is regarded as the original signal to repeat all the steps of LMD in section 1.1. Then the second pre-$PF_2(t)$ component is obtained. Similarly, the modal aliasing evaluation for the component of pre-$PF_2(t)$ is also implemented by repeating all the above steps of modal aliasing evaluation for the pre-$PF_1(t)$ component, and the $PF_2(t)$ component is then gained. Repeat all the mentioned steps to complete the whole decomposition process of the LMD-BPF, and obtain a series of $PF_p(t)$ components and $u_k(t)$.

When implementing the above modal aliasing evaluation for the PF components, if $q=1$, then it means that the obtained PF component is normal, and the modal aliasing phenomenon does not exist. In other words, the PF component does not need to be processed by the band pass filtering at this time, so there is $PF_p(t) = \mathrm{pre} - PF_p(t)$. It is extracted from the former residual signal and the decomposition process of the next PF component will be directly started.

It should be noted that, compared with LMD and direct band-pass filtering method, the LMD-BPF method proposed in this paper has its innovations. The direct band-pass filtering method is only suitable for stationary signals, while test signals in engineering are usually non-stationary, and the direct band-pass filtering method has its limitations in processing these non-stationary signals. Modal aliasing is prone to occur when non-stationary signals are processed through LMD. It cannot effectively obtain single-mode signals that can be used for modal parameter identification by using LMD. While the LMD-BPF method in this paper not only utilizes the adaptive decomposition ability of LMD to non-stationary signals, but also overcomes the defects of mode aliasing effectively. Compared with the direct band-pass filtering method, the LMD-BPF method not only makes the signal mode decomposition adaptive, but also ensures the correctness and validity of the results of the signal decomposition. Meanwhile, the LMD-BPF method effectively decomposes non-stationary signals into a series of stationary signals, and FFT-IFFT is obviously applicable to stationary signals.

1.3 Modal parameter identification

Modal parameter identification (MPI) is a significant research item for mechanical vibration analysis, and it is of great significance to learn the vibration characteristics of a mechanical system. For a multi-degree-of-freedom mechanical system, the displacement response under pulse excitation can be expressed as the sum of displacement responses of several single-degree-of-freedom systems[16-17], that is

$$x(t) = \sum_{p=1}^{k} x_p(t) = \sum_{p=1}^{k} A_p e^{-\zeta_p \omega_{np} t} \sin(\omega_{np}\sqrt{1-\zeta_p^2}\, t + \varphi_p) \tag{9}$$

where A_p, ζ_p, ω_{np} and φ_p are displacement amplitude coefficient, modal damping ratio, natural angular frequency and initial phase of the

pth mode.

For the condition of small damping, contrasting expressions (8) and (9), the instantaneous and amplitude and instantaneous phase can be expressed as:

$$a_p(t)=A_p e^{-\zeta_p \omega_{np} t} \tag{10}$$

$$\theta_p(t)=\omega_{np}\sqrt{1-\zeta_p^2}\,t+\varphi_p \tag{11}$$

Take logarithm on both sides of expression (10), there is

$$\ln a_p(t)=-\zeta_p\omega_{np}t+\ln A_p \tag{12}$$

According to expressions (11) and (12), instantaneous phase curve and logarithmic amplitude curve can be gained. Then, they are fitted using linear fitting, and the modal natural frequencies and damping ratios of structures can be identified according to the slopes of the fitted straight lines.

Therefore, the modal parameter identification method based on LMD-BPF can be summarized through the flow chart shown in Fig. 1. It mainly includes the single frequency component judgement for the pre-PF component obtained through LMD decomposition, band pass filtering processing and modal damping parameters calculation through solving the slope of logarithmic amplitude and phase.

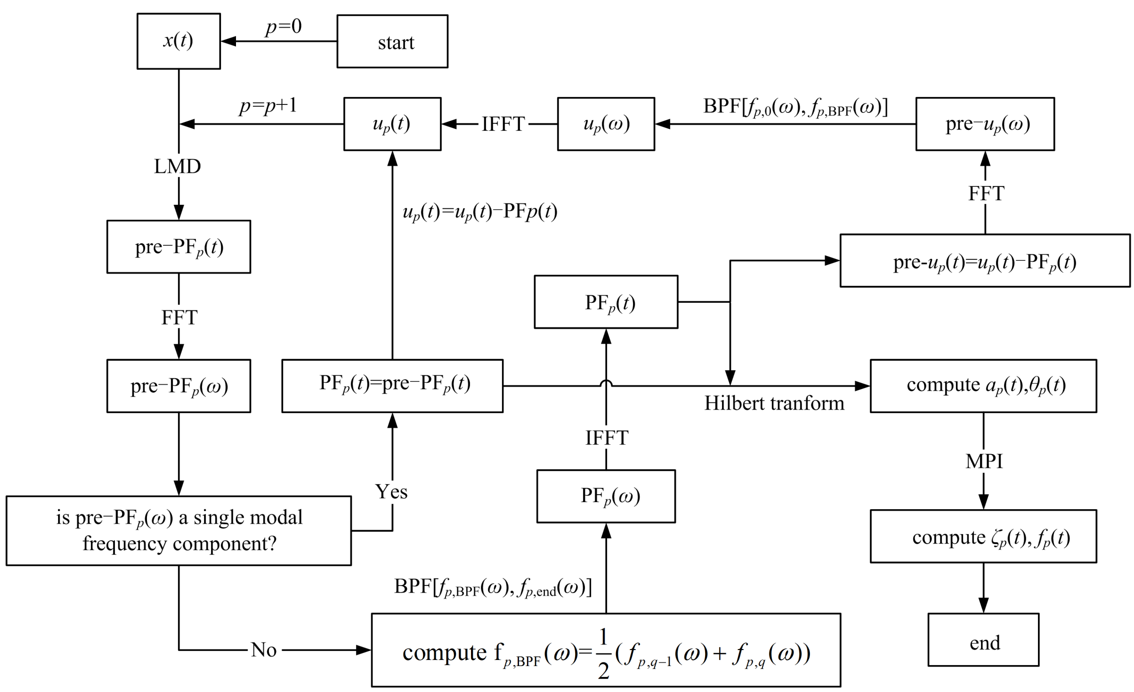


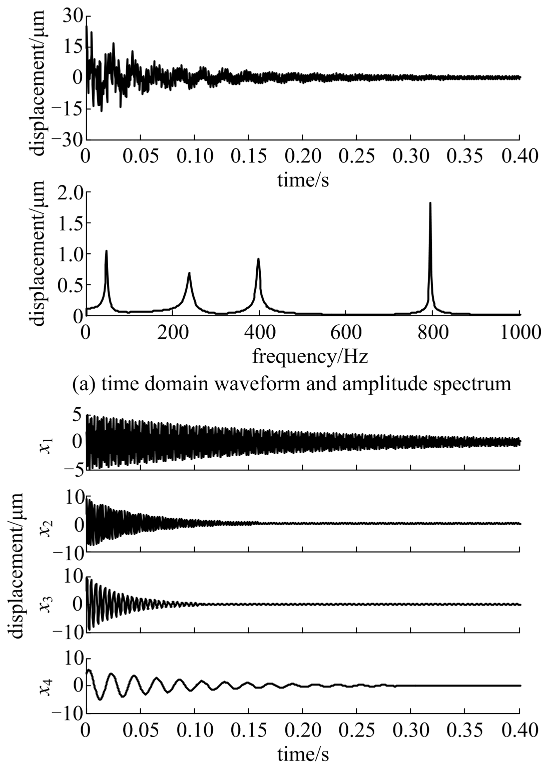
Fig. 1 The flow chart of modal parameter identification based on LMD-BPF

2 Simulation analysis

Generally, low-order modes dominate the displacement response of a mechanical system. According to expression (9), a simulation signal of displacement response is constructed as follows:

$$\begin{aligned}
x(t)&=x_1(t)+x_2(t)+x_3(t)+x_4(t);\\
x_1(t)&=5e^{-0.001\times5000t}\sin\left(5000\sqrt{1-0.001^2}\,t+\pi/10\right),\\
x_2(t)&=9e^{-0.008\times2500t}\sin\left(2500\sqrt{1-0.008^2}\,t+\pi/8\right),\\
x_3(t)&=10e^{-0.02\times1500t}\sin\left(1500\sqrt{1-0.02^2}\,t+\pi/6\right),\\
x_4(t)&=6e^{-0.04\times300t}\sin\left(300\sqrt{1-0.04^2}\,t+\pi/4\right)
\end{aligned} \tag{13}$$

The sampling frequency and sampling time of the simulation signal are 2048 Hz and 0.4 s, respectively. The time domain waveform and amplitude spectrum are shown in Fig. 2(a). From expression (13), it is clear that displacement response contains four modal components, which correspond to the four components of the simulation signal in Fig. 2(b). If each mode can be separated from the simulation signal, the modal parameters of each mode can be extracted using the modal parameter identification method of a single-degree-of-freedom system in the section 1.3.

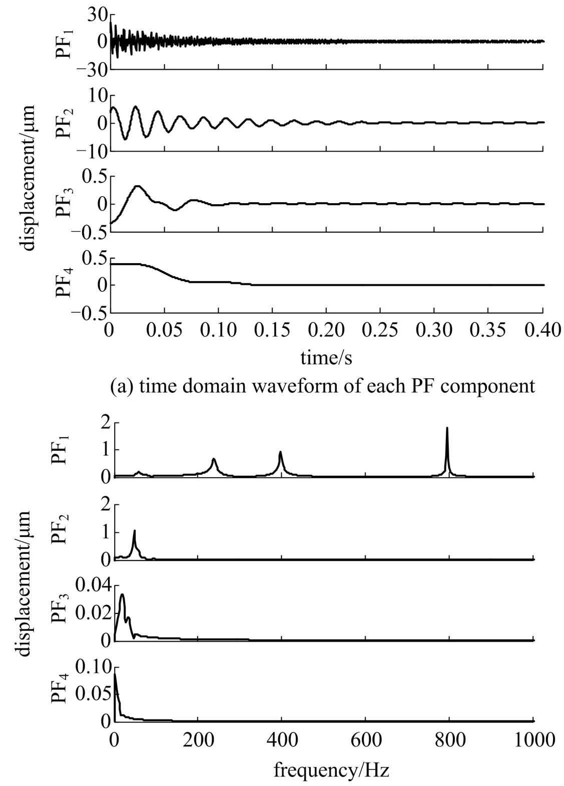


(a) time domain waveform and amplitude spectrum

(b) time domain waveform of each component

Fig. 2 Time domain waveform and amplitude spectrum of a simulation signal

The simulation signal was decomposed into four PF components using LMD method, and their time domain waveforms and amplitude spectrums were displayed in Fig. 3. Contrasting Fig. 3(a) and Fig. 2(b), it can be found that the time domain waveforms of the four PF components obtained by LMD decomposition have significant differences from those of the four components of the simulation signal. Meanwhile, from the amplitude spectrums in Fig. 3(b), it can also be found that the PF_1 component contains several modal frequencies, and the PF_2 to PF_4 components do not coincide with the corresponding frequencies of x_2 to x_4. These results suggested that, for the simulation signal, modal aliasing exists in the LMD decomposition results, and the decomposition results are not a single modal frequency component, and they do not meet the basic condition that modal parameter identification is only applicable to a single-degree-of-freedom system. Therefore, the decomposition of LMD for the displacement simulation signal failed.



(a) time domain waveform of each PF component

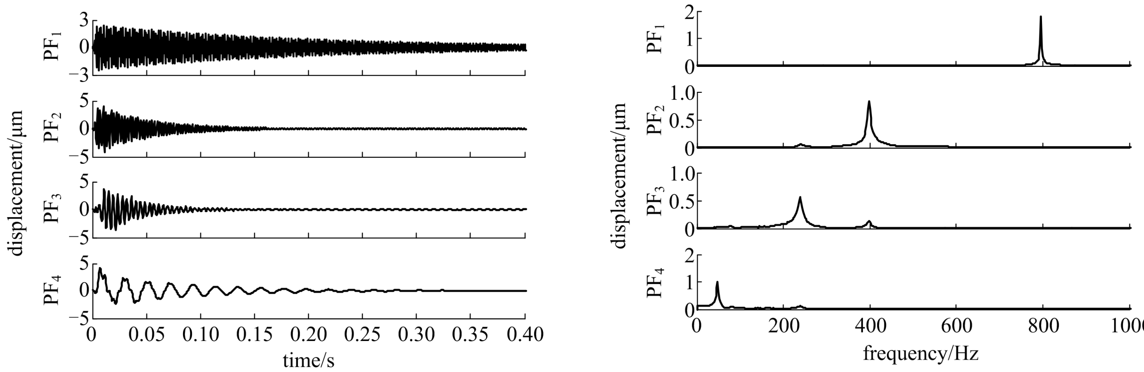
(b) amplitude spectrum of each PF component

Fig. 3 LMD decomposition results of the simulation signal

LMD-BPF method also decomposed the simulation signal into four PF components, and the corresponding time domain waveforms and amplitude spectrums were illustrated in Fig. 4(a) and 4(b), separately. The time domain waveforms of each PF component in Fig. 4(a) are in good agreement with those of each component in Fig. 2(b). Furthermore, the amplitude spectrum of each PF component shown in Fig. 4(b) is a single modal frequency component, which demonstrates that the LMD-BPF method successfully realized the separation of each mode of the simulation signal, and the correct single modal frequency components are available for the following modal parameter identification.

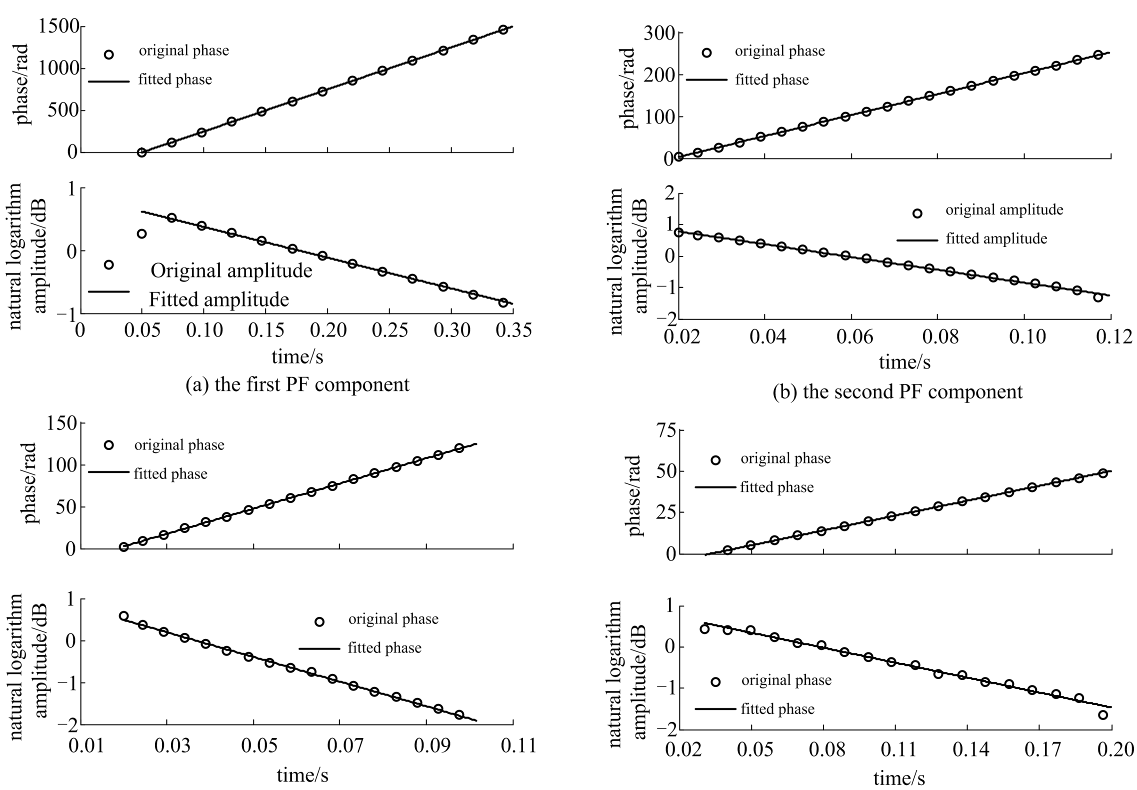
Since the single-mode components cannot be effectively obtained through LMD, the modal parameters of LMD results cannot be obtained by using formulas (11) and (12). Therefore, the modal parameters of the simulation signal identified by the LMD-BPF method can only be compared with the theoretical values.

For the four correct PF components obtained through the LMD-BPF decomposition, the instantaneous phase curves and the logarithmic amplitude curves of the four PF component were obtained, respectively, according to expressions (11) and (12). And the fitted straight lines of them were also gained through linear fitting, as shown in Fig. 5. The modal parameters of the displacement simulation signal can be calculated according to the slopes $\omega_{np}\sqrt{1-\zeta_p^2}$ and $-\zeta_p\omega_{np}$ of the fitted straight lines.



(a) time domain waveform of each PF component　　(b) amplitude spectrum of each PF component

Fig. 4　LMD-BPF decomposition results of the simulation signal



(a) the first PF component　　(b) the second PF component

(c) the third PF component　　(d) the fourth PF component

Fig. 5　Instantaneous phase and natural logarithm amplitude of each PF component after the LMD-BPF decomposition

The comparison results of the modal parameters of the simulation signal identified by the LMD-BPF method with the theoretical values were shown in Tab. 1. It can be seen that LMD-BPF method comparably accurately extracted the four modes of the simulation signal, and the calculated modal natural frequencies and damping ratios coincided with the theoretical values well. The maximum error of the modal natural frequencies emerged in the first order, with an error of 0.205%. And the maximum error of the modal damping ratios appeared in the fourth order, with an error of 2.387%.

Tab. 1 Modal parameter identification results of the displacement simulation signal

Mode	Theoretical value		LMD-BPF method		error/%	
	ω (rad/s)	ζ	ω (rad/s)	ζ	ω	ζ
4^{th}	5 000	0.001	4 999.1	0.000 98	0.017	2.387
3^{rd}	2 500	0.008	2 499.7	0.008 15	0.010	1.851
2^{nd}	1 500	0.02	1 499.6	0.019 61	0.029	1.950
1^{st}	300	0.04	300.6	0.040 19	0.205	0.476

3 Modal parameter identification researches for a guide vane

As shown in Fig. 6, compressor guide vanes were fixed with the inner casing and outer casing. The static frequencies of the guide vanes were tested under their fixed condition, and the test frequency range was from 0 to 10000 Hz. In the test, the type PCB 352B10 acceleration sensor was installed at the pressure surface of the guide vane, near the blade root and the trailing edge. The middle of the trailing edge of the guide vane at the side of the pressure surface was knocked by a small steel stick, and then the guide vane vibrated under the pulse excitation force. The vibration response signals measured by the acceleration sensor were connected into data acquisition and spectrum analysis system. The spectrum diagram was obtained through FFT analysis, and through identifying the frequency value of each spectral peak in the spectrum, the static frequencies of the guide vane within the test frequency range were gained. From each spectral peak in the spectrum diagram, the guide vane modal damping ratio of a certain order mode can be calculated employing half power bandwidth method. The collected frequency testing signal and its amplitude spectrum of the guide vane were shown in Fig. 7. From the amplitude spectrum, it can be found that there were three modes existing in the guide vane in the frequency range of 0 to 10000 Hz.

The frequency testing signal of the guide vane was decomposed into three PF components by

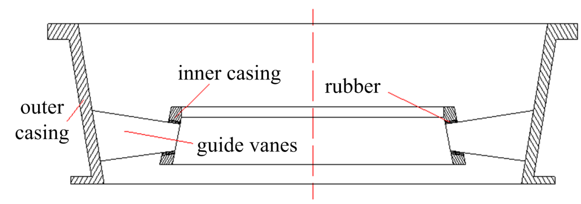


Fig. 6 The schematic diagram of compressor guide vane component

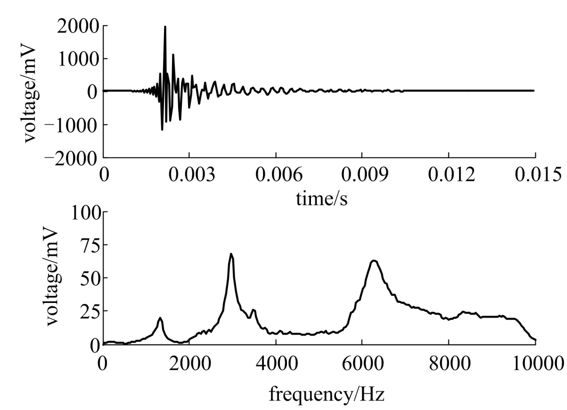
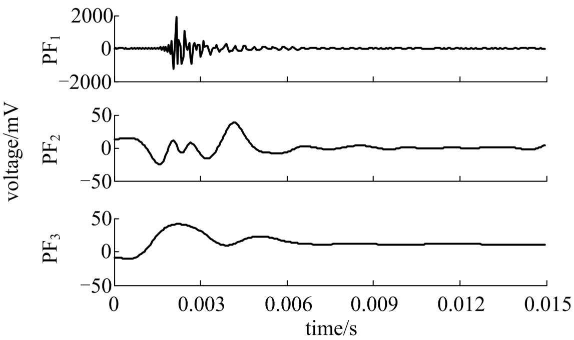


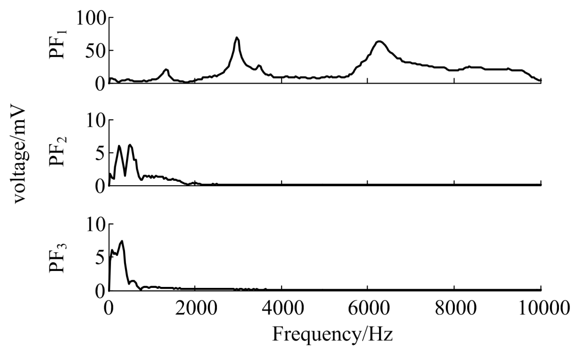
Fig. 7 Time domain waveform and amplitude spectrum of the frequency testing signal for the guide vane

LMD, and the decomposition results were demonstrated in Fig. 8. From the time domain waveform of each PF component in Fig. 8(a) and the amplitude spectrum of each PF component in Fig. 8(b), it can be observed that the phenomenon of modal aliasing and incomplete decomposition existed in the PF components of the guide vane's frequency testing signal obtained through the LMD decomposition. In other words, the three modal components of the guide vane's frequency testing signal had not been separated successfully.

Based on the above decomposition experience of the simulation signal, the frequency testing signal of the guide vane was decomposed into three

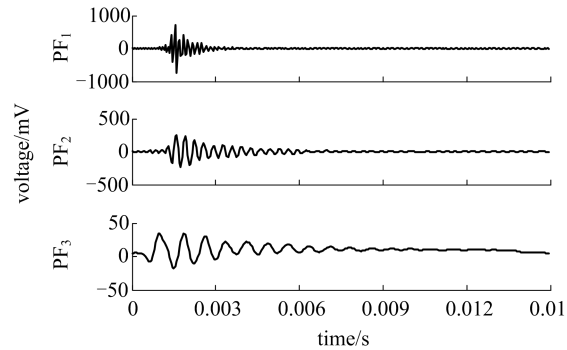


(a) time domain waveform of each PF component

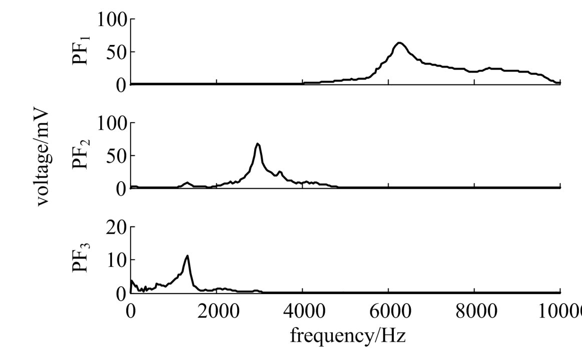


(b) amplitude spectrum of each PF component

Fig. 8 LMD decomposition results of the frequency testing signal for the guide vane



(a) time domain waveform of each PF component



(b) amplitude spectrum of each PF component

Fig. 9 LMD-BPF decomposition results of the frequency testing signal for the guide vane

PF components using the LMD-BPF method, and their time domain waveforms were shown in Fig. 9 (a) and Fig. 9 (b) were their corresponding amplitude spectrum. Contrasting Fig. 9 (b) with Fig. 7, it can be found that the LMD-BPF method also successfully realized the separation of the three modal frequencies of the guide vane's frequency testing signal, which provided useful data materials for the following modal parameter identification using modal parameter identification method of the single-degree-of-freedom system.

Similarly, because LMD fails to separate the three modal components of the guide vane's frequency testing signal successfully, the modal parameters of LMD results cannot be obtained through Eqs. (11) and (12). Therefore, the modal parameters of the guide vane's frequency testing signal identified by the LMD-BPF method can only be compared with the test values.

The modal parameters of the guide vane were identified using the proposed modal parameter identification method of the single-degree-of-freedom system, and were compared with the test modal frequencies and the modal damping ratios acquired through the half power bandwidth method. According to expressions (11) and (12), the instantaneous phase curves and natural logarithm amplitude curves of the guide vane's frequency testing signal were drawn, and the fitted straight lines of them, shown in Fig. 10, were obtained through linear fitting. Similarly, the modal parameters of the guide vane can be identified from the slopes of the fitted straight lines.

The identification results of modal parameters of the guide vane's frequency testing signal were demonstrated in Tab. 2. The test values of modal frequencies were obtained through the static frequency test of the guide vane, and the test values of modal damping ratios were calculated from the amplitude spectrum as shown in Fig. 7 through the half power bandwidth method. Due to the influence of the uncertainty and poor repeatability and some other factors, it is difficult to accurately identify modal damping. As the fundamental method of damping identification, the half power bandwidth method is also vulnerable to being affected by factors such as sampling frequency, frequency resolution and sampling analysis points[18]. Therefore, its results can only provide a reference for some other damping identification methods.

Tab. 2 Modal parameter identification results of the frequency testing signal for the guide vane

Mode	Test value		LMD-BPF method		difference/%	
	f /Hz	ζ	f /Hz	ζ	f	ζ
1st	1 328	0.040 7	1 341.0	0.040 9	0.980	0.602
2nd	2 969	0.027 0	2 971.4	0.027 2	0.080	0.549
3rd	6 250	0.046 3	6 270.9	0.046 1	0.335	0.398

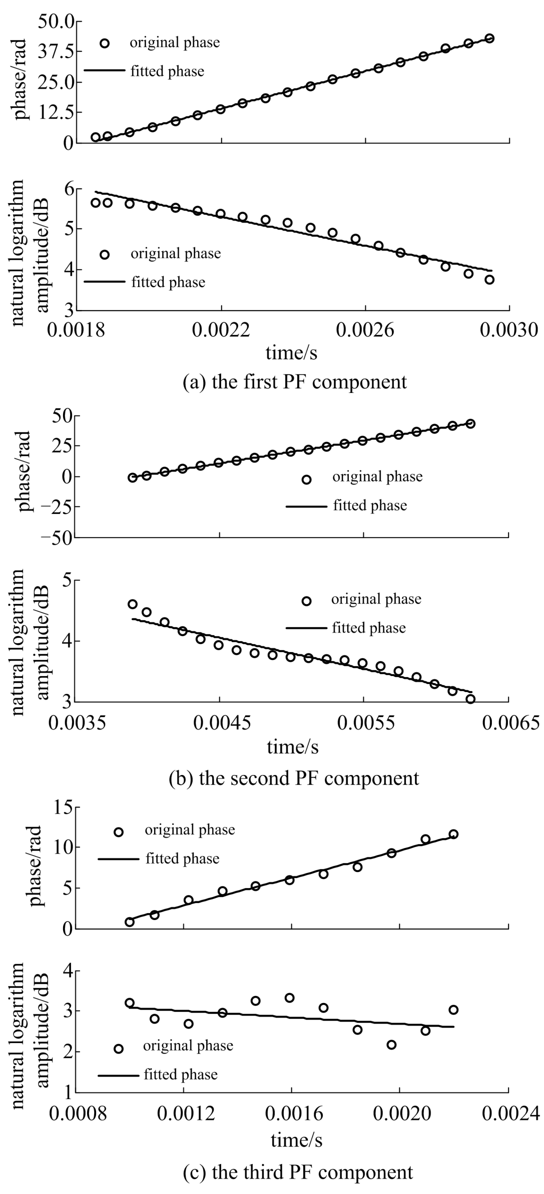


Fig. 10 Instantaneous phase and natural logarithm amplitude of each PF component after the LMD-BPF decomposition

Tab. 2 demonstrated the modal parameter identification results of the guide vane's frequency testing signal. From Tab. 2, it can be observed that the modal frequencies identified by the LMD-BPF method were close to the frequencies of the static frequency test, with the maximu error no more than 1.0%. The greatest difference of the damping ratios identified by the LMD-BPF method and the half power bandwidth method emerged in the first order, with the value of 0.602%. In conclusion, the LMD-BPF method successfully identified the modal parameters of the guide vane, and the accuracy of the identification results is also high.

4 Conclusion

Through the researches of modal parameter identification for the displacement simulation signal and the guide vane's frequency testing signal, several main conclusions can be drawn as follows:

(Ⅰ) When decomposing the displacement simulation signal and the guide vane's frequency testing signal, modal aliasing phenomenon exists in the LMD method, and the LMD method cannot effectively separate various modal frequencies from the original signal, and the signals after the decomposition do not meet the prerequisite that modal parameter identification should be carried out on a single-degree-of-freedom system.

(Ⅱ) The modal parameter identification results of the displacement simulation signal demonstrated that four calculated modal natural frequencies and damping ratios through the LMD-BPF modal parameter identification method are close to the theoretical values. The maximum error of modal natural frequencies is not more than 0.25%, and the maximum error of damping ratio is less than 2.5%.

(Ⅲ) The modal parameter identification results of the guide vane's frequency testing signal illustrated that three modes exist in the compressor guide vane in the frequency range of 0 to 10000 Hz. The LMD-BPF modal parameter identification method successfully identifies these three modes. The maximum error between the calculated modal natural frequencies of the LMD-BPF modal parameter identification method and the test frequencies of the guide vane through the static frequency test is below 1.0%. The maximum error of the calculated damping ratios of the LMD-BPF modal parameter identification method and the identified damping ratios by half power bandwidth method is less than 0.65%.

(Ⅳ) The simulation analysis and experimental verification of the modal parameter identification showed that the LMD-BPF method can accurately realize the signal decomposition and obtain correct modal components. Meanwhile, the calculated modal parameters through the LMD-BPF modal parameter identification method has high accuracy and can satisfy the requirements of engineering application. Therefore, the modal parameter identification method based on LMD-BPF could be applied in engineering to some extent.

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