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An order tracking technique for the gear fault diagnosis using local mean decomposition method

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ABSTRACT

Local mean decomposition (LMD) is a new self-adaptive time–frequency analysis method, which is particularly suitable for the processing of multi-component amplitude-modulated and frequency-modulated (AM–FM) signals. By using LMD, any complicated signal can be decomposed into a number of product functions (PFs), each of which is the product of an envelope signal and a purely frequency modulated signal from which physically meaningful instantaneous frequencies can be obtained. Theoretically, each PF is exactly a mono-component AM–FM signal. Therefore, the procedure of LMD can be regarded as the process of demodulation. While fault occurs in gear, the vibration signals would exactly present AM–FM characteristics. Therefore, targeting the modulation feature of gear fault vibration signal in run-ups and run-downs and the fact that fault characteristics found in gear vibration signal could often be related to revolution of the shaft in the transient process, a gear fault diagnosis method in which order tracking technique and local mean decomposition is put forward. The analysis results from the practical gearbox vibration signal demonstrate that the proposed algorithm is effective in gear fault feature extraction.

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1. Introduction

Gears are the important and frequently encountered components in the rotating machines that find widespread industrial applications. Therefore, the corresponding gear fault diagnosis has been the subject of extensive research.

The key step of gear fault diagnosis is the extraction of fault feature. On the one hand, the conventional gear fault diagnosis methods focus on examining the frequency spectrum analysis of vibration signal at a fixed rotation speed. Unfortunately, the information obtained thus is only partial because some faults maybe do not respond significantly at the fixed operation speed. Since faults commonly found in gear could often be related to revolution of the shaft, more comprehensive information may be acquired by measuring the gear vibration signal in the process of run-up and run-down [1]. In addition, vibration signals derived from gear in the transient process that are speed-dependent always display non-stationary feature. If frequency spectrum analysis is directly applied to the non-stationary vibration signal, frequency mixing would occur inevitably, which will bring undesirable effect to the fault feature extraction. In past research, order-tracking technique, which normally exploits a vibration signal supplemented with information of shaft speed of rotating machinery, has become one of the significant approaches for fault diagnosis in rotating machinery [2,3]. Essentially, order-tracking technique can transform a non-stationary signal in time domain into stationary one in angular domain, which can highlight the vibration information related to rotation speed and restrain the unrelated information. Therefore, order tracking is a desirable method to extract gear fault feature in the process of run-up and run-down.

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On the other hand, while faults occur in gears, the vibration signal picked up in run-up and run-down process always present the characteristics of amplitude-modulated and frequency-modulated (AM–FM). In order to extract the modulation feature of gear fault vibration signals, demodulation analysis is one of the most popular methods [4,5]. However, conventional demodulation approaches such as Hilbert transform demodulation and traditional envelope analysis have their own limitations [6]. These drawbacks include two aspects: (1) in practice most gear fault vibration signals are all multi-component AM–FM signals. For these signals, in conventional demodulation approaches, they are usually decomposed into single component AM–FM signals by band-pass filter and then demodulated to extract frequencies and amplitudes information. However, both the number of the carrier frequency components and the magnitude of the carrier frequency are hard to be determined in practice, so the selection of central frequency of band-pass filter carries great subjectivity that would bring demodulation error and make it ineffective to extract the characteristic of machinery fault vibration signal; (2) owing to the inevitable window effect of Hilbert transform, when Hilbert transform is used to extract the modulate information, the demodulation results present non-instantaneous response characteristic, that is, at the two ends of the modulated signal which has been demodulated as well as the middle part with break would produce modulation again, which makes the amplitude get fluctuation in an exponential attenuation way, and then the demodulation error would increase [7]. In order to overcome the first drawback, an appropriate decomposition method should be looked for to separate multi-component signal into a number of single component AM–FM signals before the envelope analysis. Since EMD (Empirical mode decomposition) could adaptively decompose a complicated multi-component signal into a sum of intrinsic mode functions (IMFs) whose instantaneous frequencies have physical significance [8,9], order tracking method based on EMD has been widely used in the gear fault diagnosis [10–13]. However, there still exist many deficiencies in EMD such as the end effects [14] and modes mixing [15] that are still underway. In addition, after the original signal is decomposed by EMD, the drawback produced by Hilbert transform (above mentioned) is inevitable when IMF is performed envelope analysis by Hilbert transform. Moreover, sometimes the unexplainable negative instantaneous frequency would appear when calculating instantaneous frequency by performing Hilbert transform to each IMF [16].

Local mean decomposition (LMD) is a novel demodulation analysis method, which is particularly suitable for the processing of multi-component amplitude-modulated and frequency-modulated (AM–FM) signals [16]. By using LMD, any complicated signal can be decomposed into a number of product functions (PFs), each of which is the product of an envelope signal (obtained directly by the decomposition) from which instantaneous amplitude of the PF can be obtained and a purely frequency modulated signal from which a well-defined instantaneous frequency could be calculated. In essence, each PF is exactly a mono-component AM–FM signal. Therefore, the procedure of LMD could be, in fact, regarded as the process of demodulation. Modulation information can be extracted by performing spectrum analysis to the instantaneous amplitude (envelope signal, obtained directly by the decomposition) of each PF component rather than by performing Hilbert transform to the PF components. Hence, when LMD and EMD are applied to the demodulation analysis respectively, compared with EMD, the prominent advantage of LMD is to avoid the Hilbert transform. In addition, the LMD iteration process which uses smoothed local means and local magnitudes avoids the cubic spline approach used in EMD, which maybe bring the envelope errors and influence on the precision of the instantaneous frequency and amplitude. Moreover, compared with EMD the end effect is not obvious in LMD approach because of faster algorithm speed and less iterative times [17].

Based upon the above analysis, order-tracking analysis and the recent development of demodulation techniques, LMD, are combined and applied to the gear fault diagnosis of various shaft speeds process. Firstly, order tracking technique is used to transform the gear vibration signals from time domain to angular domain. Secondly, decompose the re-sampling signal of angular domain by LMD, thus s series PF components and corresponding instantaneous amplitudes and instantaneous frequencies can be obtained. Finally, spectrum analysis is carried out to the instantaneous amplitudes of the PF component containing dominant fault information. The analysis results from the experimental vibration signal show that the proposed method can extract fault feature of the gear effectively and classify working condition accurately.

This paper is organized as follows. A theory of the LMD approach is given in Section 2. In Section 3 a gear fault diagnosis approach in which order tracking technique and LMD are combined is put forward and the practice applications of proposed method are demonstrated. In addition, the comparison between LMD-based and EMD-based method is also given in Section 3. Finally, we offer the conclusion in Section 4.

2. LMD analysis method

As mentioned above, the nature of LMD is to demodulate AM–FM signals. By using LMD a complicated signal can be decomposed into a set of product functions, each of which is the product of an envelope signal and a purely frequency modulated signal. Furthermore, the completed time–frequency distribution of the original signal can be obtained. For any signal $x(t)$, it can be decomposed as follows [16]:

(1) Determine all local extrema n_i of the original signal $x(t)$, and then the mean value m_i of two successive extrema n_i and n_{i+1} can be calculated by

$$m_i = \frac{n_i + n_{i+1}}{2} \tag{1}$$

All mean value m_i of two successive extreme are connected by straight lines, and then local mean function $m_{11}(t)$ can be formed by using moving averaging to smooth the local means m_i.

(2) A corresponding envelope estimate a_i is given by

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

Similarly, the envelope estimate a_i is smoothed in the same way and the corresponding envelope function $a_{11}(t)$ is formed.

(3) The local mean function $m_{11}(t)$ is subtracted from the original signal $x(t)$ and the resulting signal $h_{11}(t)$ is given by

$$h_{11}(t) = x(t) - m_{11}(t) \tag{3}$$

(4) $h_{11}(t)$ can be amplitude demodulated by dividing it by envelope function $a_{11}(t)$

$$s_{11}(t) = h_{11}(t)/a_{11}(t) \tag{4}$$

Ideally, $s_{11}(t)$ is a purely frequency modulated signal, namely, the envelope function $a_{12}(t)$ of $s_{11}(t)$ should satisfy $a_{12}(t) = 1$. If $a_{12}(t) \neq 1$, then $s_{11}(t)$ is regarded as the original signal and the above procedure needs to be repeated until a purely frequency modulated signal $s_{1n}(t)$ that meets $-1 \leq s_{1n}(t) \leq 1$ is derived. In other words, envelope function $a_{1(n+1)}(t)$ of the resulting $s_{1n}(t)$ should satisfy $a_{1(n+1)}(t) = 1$. Therefore

$$\begin{cases} h_{11}(t) = x(t) - m_{11}(t) \\ h_{12} = s_{11}(t) - m_{12}(t) \\ \quad\vdots \\ h_{1n}(t) = s_{1(n-1)}(t) - m_{1n}(t) \end{cases} \tag{5}$$

in which,

$$\begin{cases} s_{11}(t) = h_{11}(t)/a_{11}(t) \\ s_{12}(t) = h_{12}(t)/a_{12}(t) \\ \quad\vdots \\ s_{1n}(t) = h_{1n}(t)/a_{1n}(t) \end{cases} \tag{6}$$

where the objective is that

$$\lim_{n\to\infty} a_{1n}(t) = 1 \tag{7}$$

In practice, a variation δ can be determined in advance. If $1-\delta \leq a_{1(n+1)}(t) \leq 1+\delta$ and $-1 \leq s_{1n}(t) \leq 1$, then iterative process would be stopped.

(5) Envelope signal $a_1(t)$, namely, instantaneous amplitude function, can be derived by multiplying together the successive envelope estimate functions that are acquired during the iterative process described above.

$$a_1(t) = a_{11}(t)a_{12}(t)\cdots a_{1n}(t) = \prod_{q=1}^{n} a_{1q}(t) \tag{8}$$

where q is the times of the iterative process.

(6) Multiplying envelope signal $a_1(t)$ by the purely frequency modulated signal $s_{1n}(t)$ the first product function PF_1 of the original signal can be obtained.

$$PF_1(t) = a_1(t)s_{1n}(t) \tag{9}$$

PF_1 contains the highest frequency oscillations of the original signal. Meantime, it is a mono-component AM–FM signal, whose instantaneous amplitude is exactly the envelope signal $a_1(t)$ and instantaneous frequency is defined from the purely frequency modulated signal $s_{1n}(t)$ as

$$f_1(t) = \frac{1}{2\pi}\frac{\mathrm{d}[\arccos(s_{1n}(t))]}{\mathrm{d}t} \tag{10}$$

(7) Subtract the first PF component $PF_1(t)$ from the original signal $x(t)$ and we have a new signal $u_1(t)$, which becomes the new original signal and the whole of the above procedure is repeated, i.e. up to k times, until u_k becomes monotonic function

$$\begin{cases} u_1(t) = x(t) - PF_1(t) \\ u_2(t) = u_1(t) - PF_2(t) \\ \quad\vdots \\ u_k(t) = u_{k-1}(t) - PF_k(t) \end{cases} \tag{11}$$

Thus, the original signal $x(t)$ was decomposed into k-product and a monotonic function u_k

$$x(t) = \sum_{p=1}^{k} \mathrm{PF}_p(t) + u_k(t) \tag{12}$$

where p is the number of the product function.

Furthermore, the corresponding complete time–frequency distribution could be obtained by assembling the instantaneous amplitude and instantaneous frequency of all PF components.

3. The gear fault diagnosis method based on order tracking technique and LMD

3.1. Order tracking analysis and the corresponding fault diagnosis method

Order-tracking technique could transform a non-stationary signal in time domain into a stationary signal in angular domain by applying equi-angular re-sampling to vibration signal with reference to shaft speed. Furthermore, order spectrum can be obtained by using spectrum analysis to stationary signal in angular domain, thus the information related to rotation speed can be highlighted and the unrelated one could be restrained. Therefore, order-tracking is suitable for the vibration signal analysis of rotation machine.

There are three popular techniques for producing synchronously sampled data: a traditional hardware solution, computed order tracking (COT) and order tracking based on estimation of instantaneous frequency [18–20]. The traditional hardware approach, which uses specialized hardware to dynamically adapt the sample rate, is only suitable for the case that rotating speed of shaft is relatively smooth, thus resulting to a high cost. The method of order tracking based on estimation of instantaneous frequency has no need for specialized hardware and thus cost is relatively low, however, it has failed to analyze multiple component signal. While in practice most gear fault vibration signals exactly present the characteristic of multi-component. Therefore, this technique has little practice significance. COT technique realized equi-angular re-sampling by software, therefore it not only requires no specialized hardware, but also have no limitation for analysis signal that means it is more flexible and more accurate. Just for this reason, COT is introduced into the gear fault detection in this paper.

The step of the gear fault diagnosis method based on order tracking technique and LMD can be listed as follows:

(1) The vibration signals and a tachometer signal are asynchronously sampled, that is, they are sampled conventionally at equal time incrementsΔt;
(2) Calculate the time series t_i corresponding to equi-angular increments $\Delta\theta$ by tachometer signals;
(3) According to the time series t_i, apply interpolation to the vibration signals, thus the synchronous sampling signal, namely, stationary signal in angular domain, can be obtained;
(4) Use LMD to decompose the equi-angular re-sampling signal, thus s series PF components and corresponding instantaneous amplitudes and instantaneous frequencies can be acquired;
(5) Apply spectrum analysis to the instantaneous amplitude of each PF component, and then we have the order spectrum.

3.2. Application

Since the gear fault vibration signal in run-up and run-down process are always multiple component AM–FM signals and fault feature frequency would vary with rotation speed, the fault diagnosis method in which order tracking technique and LMD are combined would be suitable for gear fault detection.

To verify the effectiveness of the proposed method, the fault diagnosis method based on order tracking technique and LMD was applied to the experimental gear vibration signals analysis. An experiment has been carried out on the rotating machinery test rig that is used for modeling different gear faults [21]. Here we consider three working conditions that are gear with normal condition, with cracked tooth and with broken tooth. Standard gears with teeth number $z=55$ and $z=75$ are used on input and output shafts respectively, in which the crack fault is introduced into the gear on the input shaft by cutting slot with laser in the root of tooth, and the width of the slot is 0.15 mm, as well as its depth is 0.3 mm. Therefore, the mesh order is $x_{\mathrm{m}}=55$ and the fault feature order is $x_{\mathrm{c}}=1$. Figs. 1 and 2 give the rotation speed signal $r(t)$ picked up by a tachometer and vibration acceleration signal $s(t)$ of the gear with crack fault collected by a piezoelectric acceleration sensor respectively, in which the sample frequency is 8192 Hz and total sample time is 20 s, and from which we know the speed of input shaft increased gradually from 150 rpm to 1410 rpm, then decreased to 820 rpm. Meantime, the amplitude of vibration acceleration signal accordingly changed, from which a section of signal $s_1(t)$ of 5 s–7 s in the run-up progress is intercepted for further analysis. Fig. 3 gives the spectrum of $s_1(t)$ by applying spectrum analysis directly to vibration signal. For the rotation speed changes with time, the frequency mixing arises. Therefore, it is impossible to find meshing frequency and fault feature frequency in Fig. 3. As a result, actual gear working condition cannot be identified. Replace direct spectrum analysis by the order tracking method. Firstly, assume sample point per rotation is 400, namely, the maximum analysis order is 200. Secondly, angular domain signal $j_1(\theta)$ shown in Fig. 4 can be obtained by performing order re-sampling to $s_1(t)$, in which horizontal ordinate has changed from time to radian. Thirdly, the corresponding order spectrum of $j_1(\theta)$ can be calculated that is illustrated in Fig. 5, from which we can find obvious spectral peak

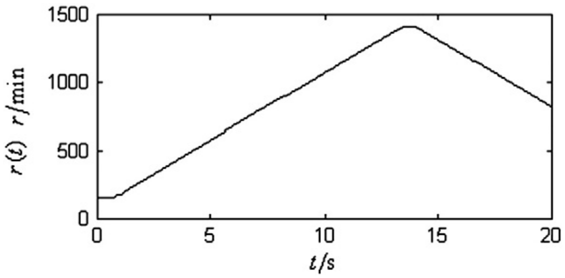

Fig. 1. The input shaft speed $r(t)$ of the cracked gear in the run-up and run-down process.

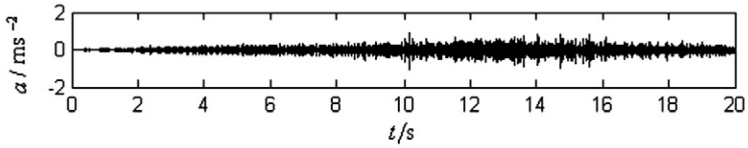

Fig. 2. The vibration acceleration signal $s(t)$ of the gear with crack fault.

values at order $O = 55$ and $O = 110$ corresponding to gear meshing order and the double. Thus it means that frequency aliasing phenomenon has been eliminated to a large degree. However, $j_1(\theta)$ is still a multiple component MA–MF signal. Therefore, side frequency band reflecting fault feature frequency is indistinct. To extract fault characteristic effectively, apply LMD to $j_1(\theta)$, thus seven PF components and a residue can be obtained shown in Fig. 6, which means LMD is a demodulation progress. Therefore, it is possible to extract gear fault feature by utilizing spectrum analysis to the instantaneous amplitude of PF component containing dominant fault information. By analysis, we know that the main failure information is included in the first PF component. Therefore, Figs. 7 and 8 give instantaneous amplitude $a_1(\theta)$ of the first PF component PF $_1(\theta)$ and the corresponding order spectrum of $a_1(\theta)$, from which it is clear that there are distinct spectral peak value at the 1st order ($O = 1$) corresponding to gear fault feature order x_c, which accords with the actual working condition of the gear.

Figs. 9 and 10 show the rotation speed signal $n(t)$ and the time domain waveform of vibration acceleration signal $s(t)$ of the gear with broken tooth respectively, in which the sample rate is 8192 Hz and total sample time is 20 s. The broken tooth fault is introduced into the gear on the input shaft by cutting slot with laser in the root of tooth. Firstly, a section of signal $s_1(t)$ of 5 s–7 s in the run-up progress is intercepted for further analysis; secondly, assume sample point per rotation is 400; thirdly, angular domain signal $j_1(\theta)$ shown in Fig. 11 can be obtained by performing order re-sampling to $s_1(t)$; fourthly, apply LMD to $j_1(\theta)$; finally, the corresponding order spectrum shown in Fig. 12 of instantaneous amplitude of the first PF component PF $_1(\theta)$ can be acquired, from which it is clear that there are distinct spectral peak value (it is bigger than that in Fig. 8) at the 1st order ($O = 1$) corresponding to gear fault feature order x_c, which accords with the actual working condition of the gear.

Similarly, we can do likewise for the normal gear. The rotation speed signal $n(t)$ and the time domain waveform of vibration acceleration signal $s(t)$ of the normal gear are listed in Figs. 13 and 14 respectively, in which the sample rate is 8192 Hz and total sample time is 20 s. After the same method mentioned above is applied to the original signal shown in Fig. 14, the results are shown in Figs. 15 and 16. Fig. 15 shows the angular domain signal $j_1(\theta)$ after performing order re-sampling to the section (5 s–7 s in the run-up progress) of the original signal. Fig. 16 shows the corresponding order spectrum of instantaneous amplitude of the first PF component, from which it is difficult to find gear fault feature order, which also accords with the actual working condition of the gear.

At present, another competing demodulation method for multi-component AM–FM signal, namely, empirical mode decomposition (EMD), already exist and have been widely used in signal demodulation analysis[7,22]. In order to compare two approaches, replacing LMD by EMD, we can do likewise using EMD for the re-sampling signals shown in Figs. 4, 11 and 15

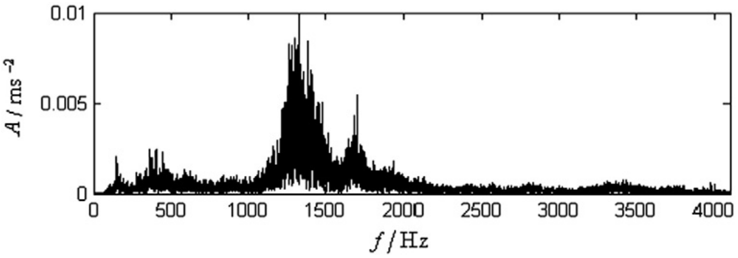

Fig. 3. The spectrum of vibration signal of the gear with crack fault.

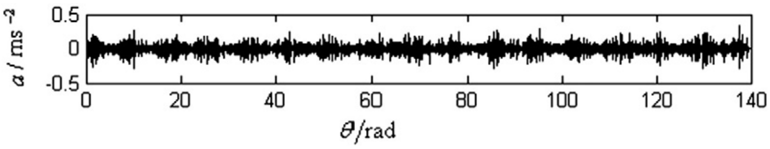

Fig. 4. The corresponding vibration acceleration signal$j_1(\theta)$ in angular domain by applying order re-sampling to$s(t)$ shown in Fig. 2.

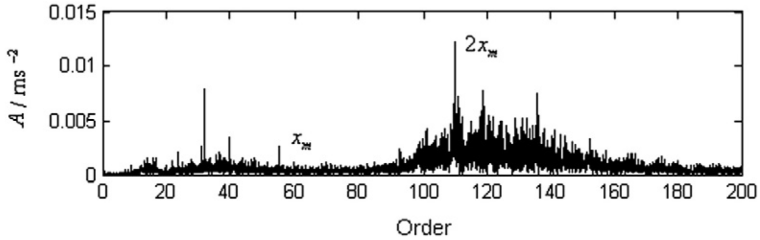

Fig. 5. The order spectrum of $j_1(\theta)$.

respectively, thus a series IMF component can be obtained. Furthermore, the corresponding instantaneous amplitude and instantaneous frequency of each IMF component can be calculated by Hilbert transform. By analysis, we know that the dominant feature information is included in the first IMF component. Therefore, spectrum analysis is only applied to the instantaneous amplitude of the first IMF component. Figs. 17–19 give the order spectrum corresponding to three vibration signals of cracked fault, broken tooth fault and normal gear, respectively, from which it is clear that order tracking analysis based on EMD can also extract gear fault feature and identify gear working condition. Although both EMD and LMD can decompose the original signal effectively, the difference between two methods still exists. Comparing to EMD method, as mentioned in Section 1, LMD have more advantages such as less iterative times, unobvious end effect and less phoniness components of the instantaneous frequency, which make it possible to use for more applications in practice.

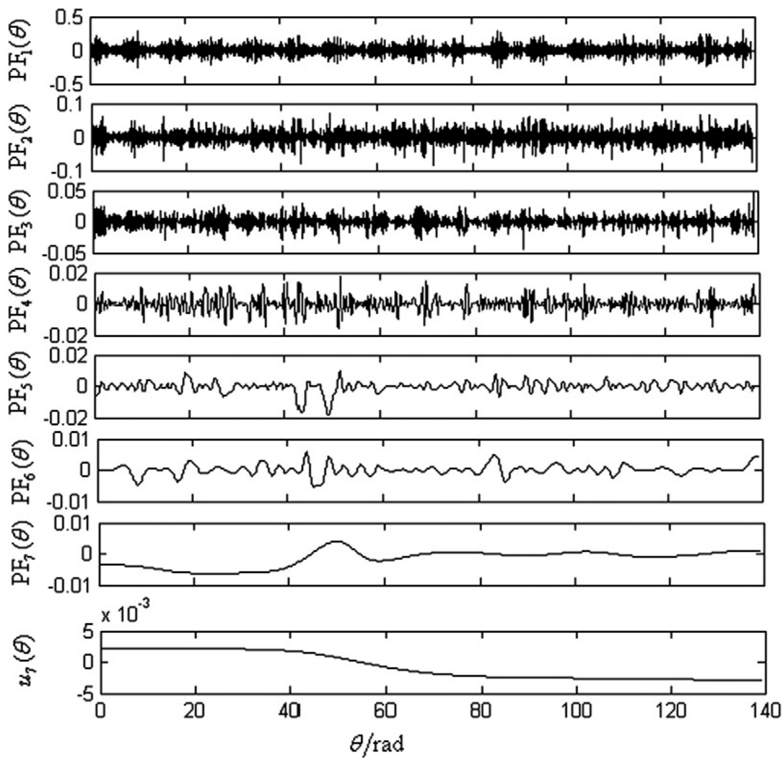

Fig. 6. The decomposition results of $j_1(\theta)$ by LMD.

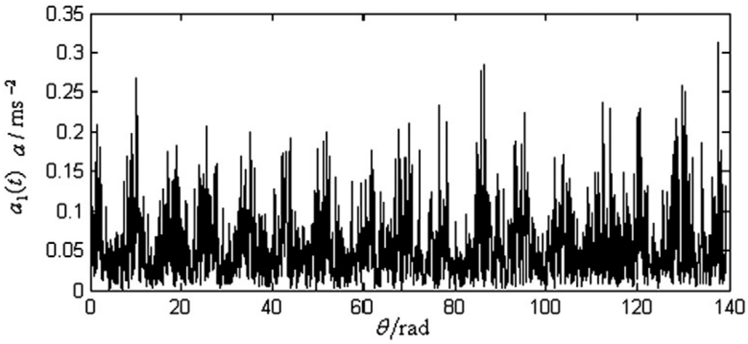

Fig. 7. The instantaneous amplitude $a_1(\theta)$ of PF $_1(\theta)$.

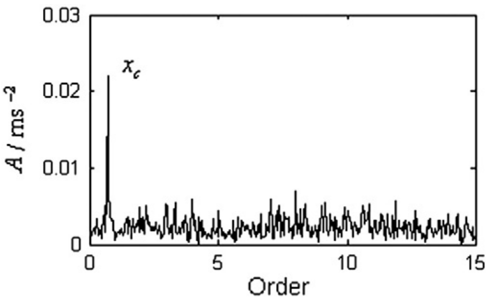

Fig. 8. The order spectrum of the first PF component shown in Fig. 6.

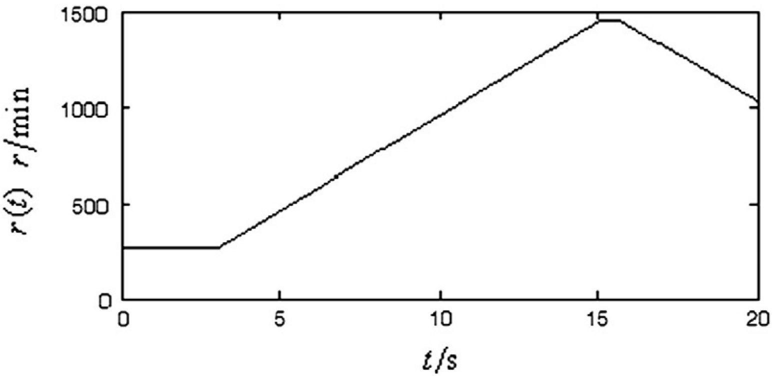

Fig. 9. The input shaft speed $r(t)$ of the gear with broken tooth in the run-up and run-down process.

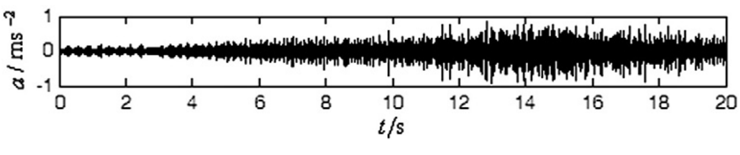

Fig. 10. The vibration acceleration signal $s(t)$ of the gear with broken tooth.

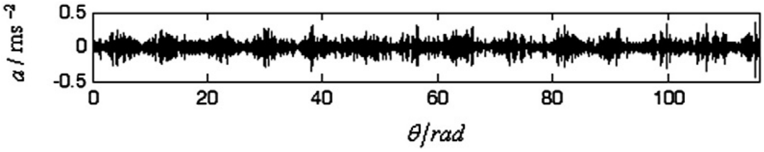

Fig. 11. The corresponding vibration acceleration signal$j_1(\theta)$ in angular domain by applying order re-sampling to$s(t)$ shown in Fig. 10.

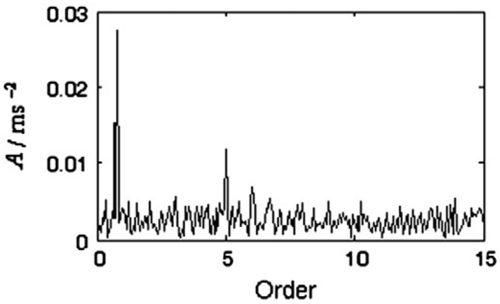

Fig. 12. The order spectrum of the first PF component of the broken gear fault vibration signal.

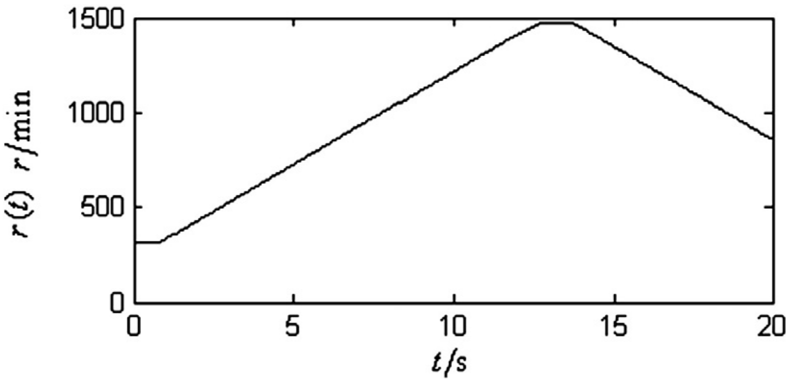

Fig. 13. The input shaft speed $r(t)$ of the normal gear in the process of the run-up and run-down.

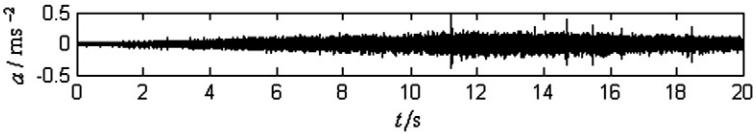

Fig. 14. The vibration acceleration signal $s(t)$ of a gear under normal state.

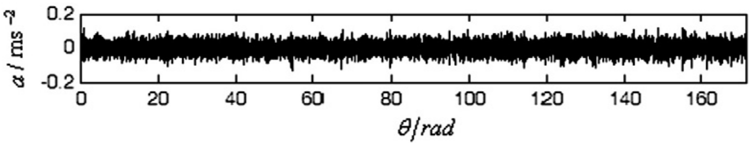

Fig. 15. The corresponding vibration acceleration signal $j_1(\theta)$ in angular domain by applying order re-sampling to $s(t)$ shown in Fig. 14.

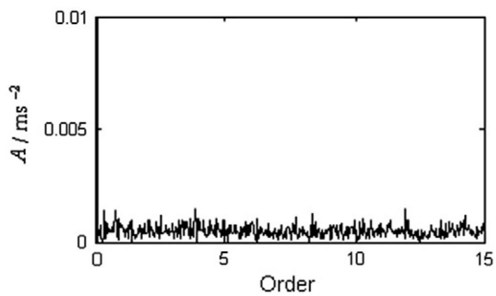

Fig. 16. The order spectrum of the first PF component of the normal gear vibration signal.

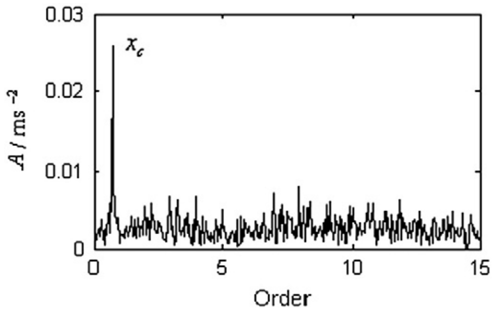

Fig. 17. The order spectrum of the first IMF component of the gear with cracked tooth by using EMD.

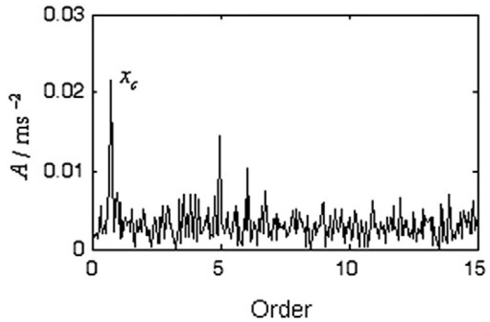

Fig. 18. The order spectrum of the first IMF component of the gear with broken tooth by using EMD.

4. Conclusion

In gear fault diagnostic technology, order tracking is a well-known technique that can be used for fault detection of rotation machinery by using vibration signals. Targeting the modulation feature of gear fault vibration signal in run-ups and run-downs and the fact that faults found in gear could often be related to shaft speed in the transient process, order tracking technique and LMD are combined to use for the gear fault diagnosis. From the theory analysis and experiment results the following points can be concluded:

(1) When vibration signal under various shaft speed condition is processed, frequency mixing resulted from conventional spectrum analysis can be overcome by introducing order tracking technique, which make the resulting spectrum line readable.
(2) Considering that the corresponding vibration signal often displays the AM–FM feature when faults occur in gear, LMD approach is applied to demodulation. By using LMD, signal can be decomposed into a number of product functions. Meantime instantaneous amplitude and instantaneous frequency of each PF component can be obtained, thus demodulation of original signal eventually is realized. Furthermore, gear fault feature can be extracted accurately by applying spectrum analysis to the instantaneous amplitude of certain PF component including dominant feature information. In the proposed method, since the instantaneous amplitude can be obtained directly from the process of LMD

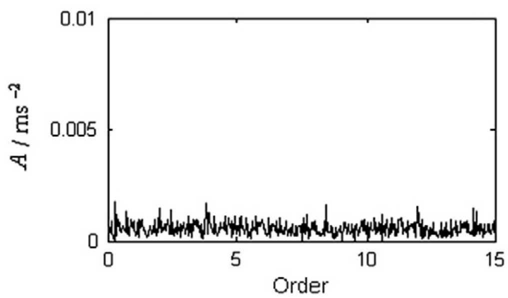

Fig. 19. The order spectrum of the first IMF component of the normal gear by using EMD.

other than using Hilbert transform, the limitations which is produced by Hilbert transform (mentioned in Section 1) can be avoided.

(3) The analysis results from experimental signals with normal and defective gears show that the diagnosis approach proposed could identify gear status-with or without fault accurately and effectively.

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