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Application of Resonance Demodulation in Rolling Bearing Early Fault Feature Extraction Based on Electronic Resonance

Zhe Wu[1] and Jianchao Zhang[2]

[1]*School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing, 100044, PR China;*
China Shijiazhuang City, Hebei Province, North Ring Road on the 17th, School of Mechanical Engineering, Shijiazhuang Tiedao University Postal Code: 050043
meishan6082@163.com
[2]*School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing, 100044, PR China;*
China Shijiazhuang City, Hebei Province, North Ring Road on the 17th, School of Mechanical Engineering, Shijiazhuang Tiedao University Postal Code: 050043
zhangjianchao@yeah.net E-mail

Abstract

Resonance demodulation is a commonly used rolling bearing fault diagnosis method, but resonance frequency of traditional resonance demodulation technology has a certain discreteness due to differences in terms of processing, testing and installation of sensor to collect fault information, so parameter of band-pass filter needs manual pre-determination. At the same time, as information of early bearing minor fault is often submerged in strong background noise, signal to noise ratio is low. Application of traditional resonance demodulation method to improve signal to noise ratio is with limited capability, and diagnosis effect is not obvious. This paper makes use of the equivalence of electrical resonance system and mechanical resonance system and gains resonance of sensor output signal through electrical resonator, which breaks through shortcomings of traditional method, achieve ultra narrow brand high-resolution detection, and improves signal to noise ratio of fault feature signal. Finally, verification is done through simulation fault bearing signal and actually collected fault signal. The results proves validity and effectiveness of the proposed method which has an important guiding significance for engineering

Keywords: *resonance demodulation; rolling bearings; electronic resonance; fault diagnosis*

1. Introduction

Rolling railway is one of the most critical components in freight wagon bogies, but also prone to damage. Many major faults are caused by bogie rolling bearing damage, so service life of rolling bearings has a direct impact on train stability and security. In addition, most of frequent rolling bearing faults exist in early bearing life cycle in the form of local defect and most are potential damage which is difficult to be found. Therefore, research on extraction of early train rolling bearing fault feature has important scientific significance and application value [1-3].

Traditional resonance demodulation technology is one of basic methods of modern rolling bearing fault diagnosis. It mainly uses envelope analysis to extract vibration impulse signal, selects modulated signal with fault information through band-pass filter, then separates fault signal from modulated signal with envelope demodulation technology, and then diagnoses whether bearing has fault and fault types [4] based on

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whether there is significant bearing fault feature frequency in the frequency spectrum. As information of early bearing minor fault is often submerged in strong background noise, signal to noise ratio is low. Application of traditional resonance demodulation method to improve signal to noise ratio is with limited capability, and diagnosis effect is not obvious. Therefore, effective signal processing technology should be adopted to improve signal to noise ratio and highlight fault feature. Meanwhile, weak low-frequency repeated impulse signal caused by early bearing fault submerged in strong background noise should be separated, which requires that band-pass filter has a sufficiently narrow bandwidth. However, traditional resonance demodulation technology features high frequency resolution at low frequency stage and low frequency resolution at high frequency stage, thus unable to meet high frequency narrow band requirement for band-pass filter in early weak fault signal. At the same time, in traditional resonance demodulation method, band-pass filter parameter setting requires a lot of experiences, which leads to limited promotion [5] of traditional resonance demodulation in practical engineering applications. Therefore, effective signal noise reduction technology must be adopted to improve signal to noise ratio and highlight fault feature. Commonly used noise reduction methods include traditional filter noise reduction, wavelet noise deduction, *etc.* Wavelet noise deduction enjoys such advantages as multi-resolution, *etc.*, but wavelet noise deduction effect largely depends on the choice of basis function and threshold, and therefore requires that designer has a wealth of experiences.

Meanwhile, early bearing weak fault has complex signal frequency components, so it is difficult to see whether fault is present or not through traditional resonance demodulation only via sensor signal. Nonetheless, by organic combination of fault signal and electrical resonator via sensor, early fault feature frequency can be well demodulated. When center frequency of electrical resonator is equivalent to resonance frequency of mechanical system, in fact, it is equivalent to two high-frequency resonance, thus doubling signal to noise ratio and enhancing robustness of signal. At the same time, electrical resonator can centralize high frequency vibration signal generated by weak fault impulse to resonator center frequency for amplification, so it enjoys more significant effect [6-7] for early demodulation bearing weak fault signal [6-7].

This paper presents a resonance demodulation method based on electrical resonance for early bearing fault weak feature signal. First of all, use the equivalence of electrical resonance system and mechanical resonance system, undertake fast spectral kurtosis processing of generalized resonance signal acquired by sensor, determine electrical resonator parameter according to fast spectral kurtosis figure self-adaption, and gains resonance of synthesized signal: wide band fault signal is greatly strengthened at resonant frequency of acceleration sensor, and then separate high frequency inherent vibration through resonator with center frequency equivalent to inherent frequency. Obtain output signal after resonance gain, and then undertake Hilbert envelope demodulation processing. Verify the algorithm through digital signal simulation analysis and experimental analysis. Result shows that it overcomes traditional method's limited capacity to improve signal to noise ratio, solves the problem that traditional resonance demodulation method requires manual pre-determination of filter parameter, and that the improved method can accurately extract early rolling bearing weak fault feature signal, which verifies correctness and validity of this method and has important significance for engineering practice.

2. Introduction to Basic Method

2.1. Equivalence of Mechanical and Electrical Resonance System

Due to inherent characteristic of mechanical system, some parameters of acceleration sensor has certain discreteness, which produces difficulty in resonance demodulation detection. The method described in this paper can use equivalence of mechanical resonance system and electrical resonance system, and take electrical resonance system as subsequent correction system of mechanical resonance system, so that parameters can be centralized to facilitate further processing [8-9].

Mechanical resonance system and electrical resonance system are two totally different systems in nature, but the two systems' response to excitation can be described with similar or even identical differential equation. Draw an analogy of mechanical quantity in mechanical resonance system and eclectic quantity in circuit, then equivalent analog circuit of mechanical system can be obtained. Describe mechanical resonance system problem with equivalent analog circuit. Currently, in traditional resonance demodulation method, band-pass filter is widely used to extract fault frequency component, while in resonance demodulation method based on resonance, electrical resonator is adopted to extract fault frequency component. For band-pass filter and electrical resonator with center frequency of w_0 and quality factor of Q, the transfer function can be expressed as:

$$H(s) = \frac{s\frac{w_0}{Q}}{s^2 + s\frac{w_0}{Q} + w_0^2} \tag{1}$$

The relationship between center frequency w_0 and bandwidth B may be expressed as:

$$B = \frac{w_0}{Q} \tag{2}$$

Implement Laplace transformation of mechanical resonance system and electrical resonance system respectively and obtain the two's expression in s domain:

$$H_m(s) = \frac{x_o(s)}{x_i(s)} = \frac{1}{\frac{m}{k}*s^2 + \frac{\delta}{k}*s + 1} \tag{3}$$

$$H_p(s) = \frac{v_o(s)}{v_i(s)} = \frac{1}{LC*s^2 + \frac{L}{R}*\mathrm{s}+1} \tag{4}$$

In addition, from s domain perspective, whether it is mechanical resonance system or electrical resonance system, relationship between system input and output at s domain can always be denoted by a second order function, which means that the two has equivalence in s domain. Therefore, electrical resonance system can be used to extract fault signal in replace of mechanical vibration system. At the same time, electrical resonance system is with small size, low cost, high stability and facilitates digital signal processing and other further processing. Due to these advantages, it is widely applied in engineering practice.

2.2. Electrical Resonance

This paper adopts series resonance system for analysis [10] of electrical resonance system. Loop equation can be expressed as:

$$I = \frac{U_s}{Z_s} = \frac{U_s}{r + j\left(wL - \dfrac{1}{wC}\right)} \tag{5}$$

When w meets $w_0 = \frac{1}{\sqrt{LC}}$, circuit resonance occurs.

The main role of resonance circuit is frequency selecting. Frequency of signal U_s is varied, inductive reactance jwL and capacitive reactance $1/jwC$ are also varied. With increase of frequency f, inductive reactance increases while capacitive reactance decreases. When applied signal frequency is equal to w_0, circuit inductive reactance equals to capacitive reactance, loop is in pure resistance state, then current is maximum and resonance occurs; when applied signal frequency diverts from resonance frequency, circuit reactance increases. The greater the detuning, the smaller the loop current, so frequency selecting effect is achieved.

2.3. Process of the Method in This Paper

Adapt resonance technology into adaptive resonance demodulation method and propose resonance demodulation method based on resonance. The specific steps are as follows:

①Draw fast kurtosis figure for signals acquired with acceleration sensor, obtain center frequency and bandwidth of maximum kurtosis;

②Adaptively determine electrical resonator parameter according to fast kurtosis figure and gain resonance of signal;

③Envelope detection: Implement envelope detection of resonance signal passing band-pass filter, and obtain a pulse train consistent with fault impulse frequency;

④Low-pass filter: Through low-pass filter, signal after envelope detection can be removed with residual relatively high frequency interference noise, retaining fault signal component with relatively low frequency component;

⑤Spectrum analysis: Apply power spectrum calculation, analyze fault point from the power spectrum figure, compare with bearing fault feature frequency, and then conduct bearing fault state recognition.

3. Simulation Analysis

The simulation model adopts rolling bearing inner race pitting fault model [13-14]:

$$\left.\begin{aligned} x(t) &= s(t) + n(t) = \sum_i A_i h(t - \mathrm{i}T - \tau_\mathrm{i}) + n(t) \\ A_i &= A_0 \cos(2\pi f_c t + \varphi_A) + C_A \\ h(t) &= e^{-Bt}\cos(2\pi f_n t + \varphi_w) \end{aligned}\right\} \tag{9}$$

Wherein: $s(t)$ refers to system inherent frequency;

f_n refers to oscillation attenuation signal of oscillation frequency.

Set system sampling frequency F_s=51200Hz, rotating frequency f_r=7Hz, inner ring passing through frequency f_i=67,Hzsystem inherent frequency f_n=5900Hz, constant A_0=1, C_A=1,Φ_A=0 and Φ_w=0.Simulation fault signal and its spectrum are as shown in Figure 1 and Figure 2 respectively.

Electronic resonance adopts the resonance system made of R,L and C in series, whose transmission function is:

$$H(\mathrm{j}w) = \frac{RC \times \mathrm{j}w}{L \times (\mathrm{j}w)^2 + RC \times \mathrm{j}w + 1} \tag{10}$$

According to the resonance system's demands for 5.9KHz center frequency and 1KHz bandwidth, we can get the resonance system's transmission function expression for 5.9KHz center frequency and 1KHz bandwidth as follows:

$$H\left(\mathrm{j}w\right)=\frac{a_1\times \mathrm{j}w}{b_1\times\left(\mathrm{j}w\right)^2+b_2\times \mathrm{j}w+b_3} \tag{11}$$

Wherein,a_1=4.5721×10^{-6},b_1=7.2768×10^{-10},b_2=4.5721×10^{-6}, b_3=1.Fault signal and its spectrum after resonance processing are as shown in Figure 4 respectively.

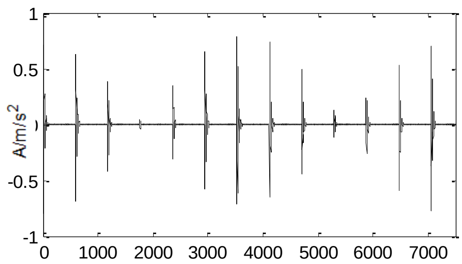
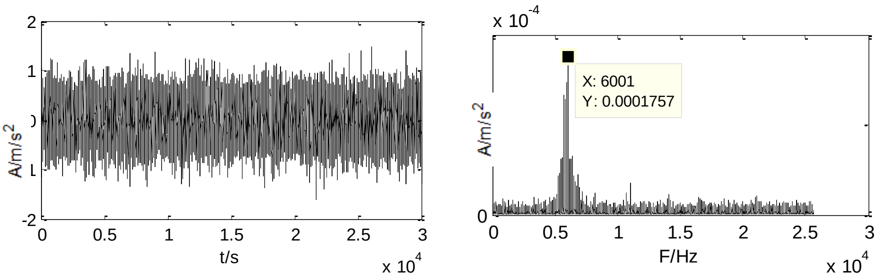


Figure 1. Time Wavefor of Shocking Component



(a) Time Domain Signal (b) Frequency Domain Signal

Figure 2. Waveform of Simulation Signal

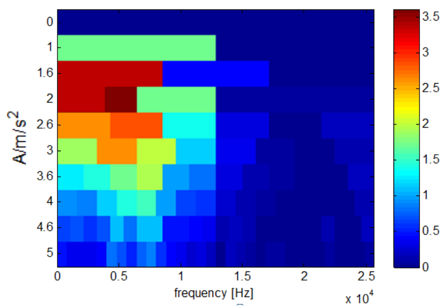
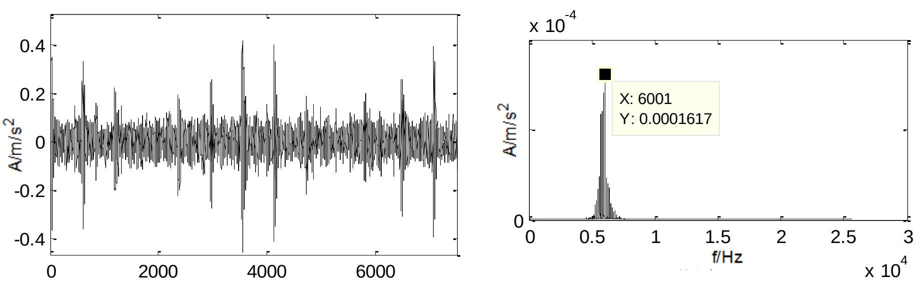
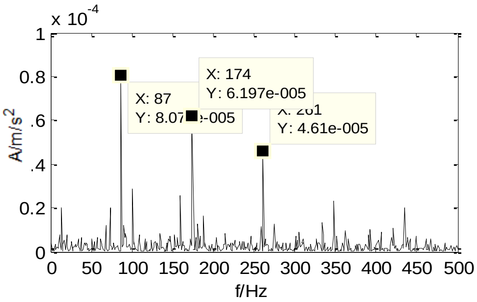


Figure 3. The Fast Kurtogram



(a) Resonance Signal Time-domain Simulation Gain (b) Resonance Gain Signal Spectrum



(c) Envelope Spectrum

Figure 4. Improved Resonance Demodulation Method Analysis

Figure4 Adaptive resonance spectrum signal demodulation method of envelope analysis

Next, conduct kurtosis calculation (Figure 3) of signal. The result shows that the maximum of spectral kurtosis is 3.5, and resonance center frequency is automatically determined to be 5900Hz. Signal spectrum after envelope demodulation shown in Figure 4 (c) reveals clearly fault frequency, which is mainly due to improvement of signal to noise ratio by resonance gain processing. When signal to noise ratio is relatively low, resonance demodulation algorithm based on resonance can still achieve satisfactory results.

4. Experimental Verification

4.1. Wheel Bearings Bench

To further verify the correctness of resonance demodulation processing with resonance method, fault bearing experimental data collection has been carried out, and the experiment, based on certain wagon's fault diagnosis test bench, has carried out vibration test on wagon 197726 bearing. The test bench adopts closed gantry frame structure, which supports loading and running-in of wheel set. The test bench is as shown in Figure 5 the experiment uses Y112M-4 three-phase asynchronous motor, and attaches CA-YD-189 piezoelectric acceleration sensor to the frame through magnetic base adsorption in the experimental process. Data acquisition equipment are provided by National Instruments (NI) Ltd., mainly including NI PXle-1082 backplane, NI PXle-8108 embedded controller and NI PXle-4496 high-precision data acquisition module, the sampling frequency is 51200, and the sampling length is 10s.

(a) Bench (b) Inner Bearing Failure

Figure 5. Freight Train Rolling Bearing Fault Simulation Platform

The test bench adopts RD_2 wheel set and matching 197726 double-row tapered rolling bearing. Its main shape parameters and working conditions during experiment are as shown in Table 1 and Table 2.

Table 1. Main Shape Parameters of Wagon 197726 Rolling Bearing

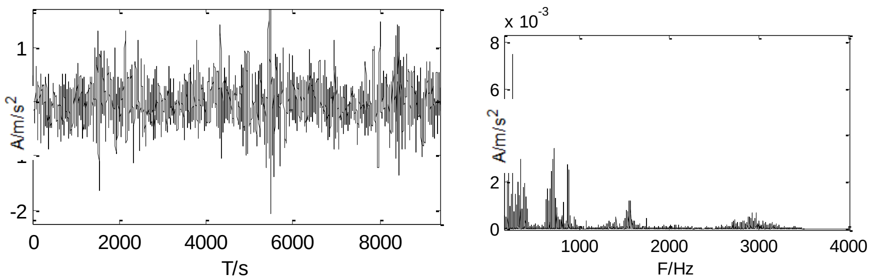
Roller diameter d/mm	Pitch diameter D/mm	Contact angle α /°	Number of rollers/ pieces
176.29	24.74	8.833	20

Table 2. Working Conditions During Experiment

Fault location	Revolving speed /(r/min)	Sampling frequency/Hz	Sampling number	Fault feature frequency /Hz
Inner ring	463	51200	102400	87.9

4.2. Analysis of Experimental Results

Acquire bearing fault time-domain signal and its spectrum by a piezoelectric sensor, as shown in Figure 6. Then conduct kurtosis calculation of signal (Figure 7). The result shows that the maximum of kurtosis is 35, and electrical resonator center frequency is automatically determined to be 6000Hz. Process it with resonance method resonance demodulation, and obtain time-domain signal and its spectrum as shown in Figure 8. Conduct envelopment analysis of demodulated signal, as shown in 8 (c). Signal frequency spectrum after envelope analysis in traditional resonance demodulation method is shown in Figure 9.



(a) Time Domain Signal (b) Frequency Domain Signal

Figure 6. Waveform of Test Signal

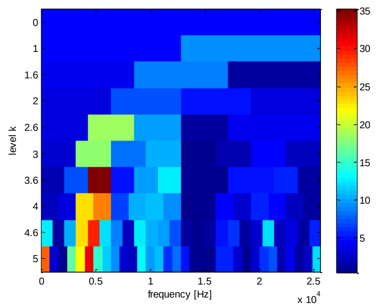
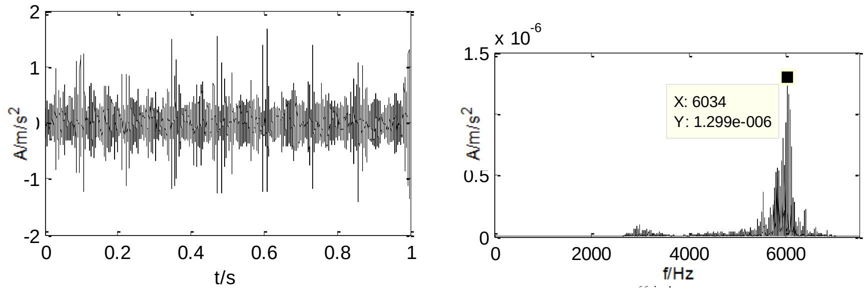
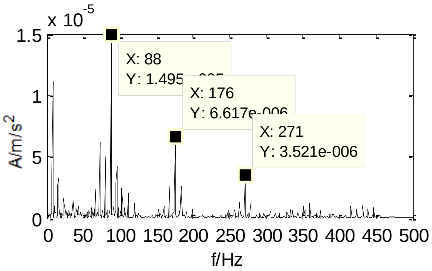


Figure 7. The Fast Kurtogram



(a) Resonance Signal Time-domain Simulation Gain (b) Resonance Gain Signal Spectrum



(c) Envelope Spectrum

Figure 8. Improved Resonance Demodulation Method Analysis

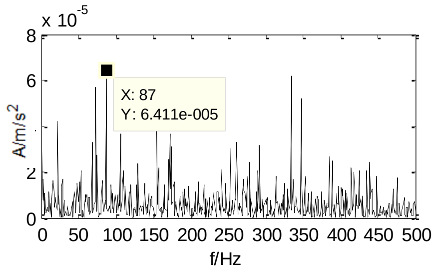


Figure 9. Adaptive Resonance Spectrum Signal Demodulation Method of Envelope Analysis

Figure 7 shows sensor raw output signal and its spectrum with clearly observed resonant frequency and its harmonic component. In envelope analysis of this signal, it hard to tell fault feature frequency 87.9Hz. Figure 8 shows signal and its spectrum after resonance processing. Separate signal within 1KHz bandwidth near the resonant frequency, and then conduct envelope analysis of this signal. Signal after envelope analysis is shown in Figure 8 (c), from which it can be seen that inner ring fault feature frequency 87.9Hz and its frequency doubling 176Hz, 264Hz are with very significant features. Figure 9 shows signal spectrum after envelope analysis in adaptive resonance demodulation method. Based on comparative analysis, harmonic ware of various orders in adaptive resonance demodulation method shown in Figure 9 persists. The processed signal is with low signal to noise ratio, which interferes extraction of fault feature frequency and directly affects accuracy of early bearing fault diagnosis. A comparison of the experimental data proves that the proposed method effectively improves signal to noise ratio and enhances signal robustness. Thus, validity and feasibility of the proposed method can be verified.

Through the above comparative analysis, it can be known that the method proposed in this paper is with better noise reduction capability, and can more effectively filter out noise component in signal while preserving useful components in it.

5. Conclusion

This paper studies application of resonance demodulation method based on resonance in extraction of early freight wagon rolling bearing fault feature. By gaining resonance of sensor output signal with electrical resonator, it overcomes shortcomings of traditional resonance demodulation method, able to achieve ultra narrow band high resolution detection and improve signal to noise ratio of fault feature signal. For early rolling bearing fault and environment with low signal to noise ratio, it is difficult to extract fault feature by applying traditional resonance demodulation method. However, through resonance demodulation method based on resonance, an accurate diagnosis of this type of fault can be obtained. Meanwhile, early bearing weak fault has complex signal frequency components, so it is difficult to see whether fault is present or not through traditional resonance demodulation only via sensor signal. Nonetheless, by organic combination of fault signal and electrical resonator via sensor, early fault feature frequency can be well demodulated. Finally, verification is done through simulation fault bearing signal and actually collected fault signals. The results proves validity and effectiveness of the proposed method which has an important guiding significance for engineering practice.

Acknowledgements

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Authors

Zhe Wu, Beijing Jiaotong University, Ph.D. The main research direction: Fault diagnosis of rotating machinery, nonlinear dynamics

