Application of Resonance Demodulation in Rolling Bearing Fault Diagnosis Based on Electronic Resonant

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Abstract: The resonance demodulation is an important method in rolling bearing fault feature extraction and fault diagnosis. But in the traditional resonance demodulation method, the resonant frequency of the accelerometer sensing fault information is discrete to some degree due to processing, debugging and installing factors, and the parameters of the band-pass filter are in need for defining beforehand. Meanwhile, as the message generated by bearing early minor failure is often submerged in strong background noise, the SNR is low, the capacity to apply traditional resonance demodulation method to improve the SNR is limited, and the diagnosis effects are not obvious enough. This paper makes use of the equivalence between the electronic resonant system and the mechanical resonance system and conducts resonant gain for sensor output signal using electronic resonators, overcoming the shortcomings of the traditional methods, realizing a UNB high-resolution detection and improved fault feature signal SNR. Besides, the effectiveness of the proposed method has been validated by simulations and experiments, which possess important guiding significance for the engineering practice.

Keywords: Electronic resonance, Fault diagnosis, Resonance demodulation, Rolling bearings.

INTRODUCTION

Rolling bearing is one of the most critical components of wagon bogie, and is also a component prone to be damaged. Many major faults are caused by damage of bogie rolling bearing, so the service life of rolling bearing has a direct impact on train running stability and safety. Besides, most of the frequent faults of rolling bearings exist in early bearing life cycle in the form of local defects, and most of them are potential damages, extremely hard to find in early stage. Therefore, the study on train rolling bearing early fault feature extraction has very important scientific significance and application value [1-5].

Traditional resonance demodulation technology is one of the basic methods in modern rolling bearing fault diagnosis, which mainly uses envelope analysis for shock and vibration signal extraction, selects modulating signal containing fault message through band-pass filter, separates fault signal from modulating signal with envelope demodulation technology, and then diagnoses whether there is any bearing fault and confirms fault type according to whether there is any obvious characteristic frequency of the bearing fault in its frequency spectrum [9-11]. However, as the message generated by bearing early minor failure is often submerged in strong background noise, the SNR is low, the capacity to apply traditional resonance demodulation method to improve the SNR is limited, and the diagnosis effects are not obvious enough. Therefore, it is required to use an effective signal processing technology to improve the SNR and highlight fault feature. Besides, it is also required to separate weak low-frequency repeated shock signal caused by early bearing faults from strong background noise, for which the band-pass filter must have a bandwidth narrow enough. Traditional resonance demodulation technology has a high frequency resolution at a low-frequency stage and a low frequency resolution at a high-frequency stage, so it cannot meet the demands for high-frequency narrowband band-pass filter in early weak fault signal.

Meanwhile, as bearing early weak fault signal frequency components are complex, it is hard to judge if there is any fault solely through traditional resonance demodulation with sensor signal. However, the organic combination of fault signal through sensor and electronic resonator can demodulate early fault feature frequency well. When the center frequency of electronic resonator is equal to the resonance frequency of the mechanical system, it is, in fact, equivalent to twice of high-frequency resonance; in this way, the SNR is doubled, enhancing signal robustness; meanwhile, the electronic resonator may collect high-frequency vibration signal caused by weak fault impact to the center frequency of resonator for amplification, so the effects are more prominent in demodulation of bearing early weak fault signal.

This paper, for bearing early fault weak feature signal, proposes a resonance demodulation method based on electronic resonance, which, taking advantage of the equivalence between the electronic resonance system and the mechanical resonance system, first processes generalized resonance signal collected by the sensor and acquires output signal with fixed resonance frequency, and then carries out resonance demodulation processing and verifies this algorithm through digital signal simulation analysis and experimental analysis. The results show that it has overcome the limitation of capacity to improve the SNR with traditional method and can accurately extract rolling bearing early weak fault feature signal, verifying the correctness and

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effectiveness of this method, and having an important guiding significance for engineering practice.

1. INTRODUCTION TO BASIC METHOD

1.1. Equivalence of Mechanical and Electronic Resonance System

Due to inherent feature of the mechanical system, some parameters of the acceleration sensor show certain discreteness, forming difficulties for resonance demodulation detection. The method described in this paper can take advantage of the equivalence between the mechanical resonance system and the electronic resonance system [6] and use the electronic resonance system as the subsequent correction system of the mechanical resonance system, so that parameters can be concentrated for subsequent processing.

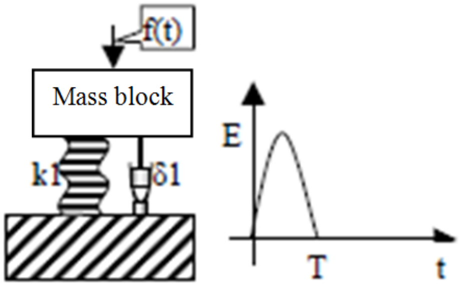

Fig. (1). Single-DOF mechanical resonance system.

The external drive refers to *f(t)*, while the response signal of the single-DOF mechanical resonance system model refers to $x_0(f)$, as shown in Fig. (**1**). According to Newton's second law, the system's differential equation of motion can be expressed as:

$$\frac{m1}{k1}\times\frac{\partial^2 x_o(t)}{\partial t^2}+\frac{\delta}{k}\times\frac{\partial x_o(t)}{\partial t}+x_o(t)=x_i(t) \tag{1}$$

Wherein, $m1$ refers to the weight of the mass block, while $k1$ refers to the elastic coefficient.

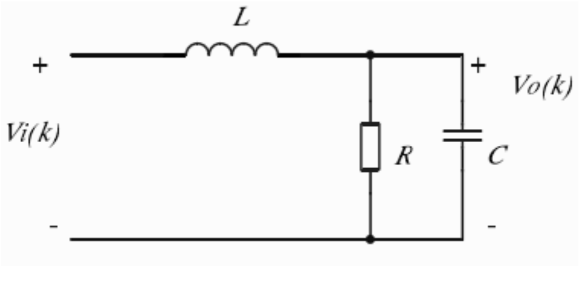

Fig. (2). Electronic resonance system.

The electronic resonance system is shown in Fig. (**2**), its drive signal refers to $v_i(t)$, while the response signal refers to $v_i(t)$. According to Kirchhoff current law, the system's differential equations of state can be expressed as:

$$LC\times\frac{\partial^2 v_o(t)}{\partial t^2}+\frac{L}{R}\times\frac{\partial v_o(t)}{\partial t}+v_o(t)=v_i(t) \tag{2}$$

Wherein, R, L and C respectively mean resistance, inductance and capacitance.

The mechanical resonance system and the electronic resonance system are two completely different systems, but both systems can use similar or even identical differential equations to describe their response to drive, analog the mechanical quantity in the mechanical resonance system with the electric quantity in the circuit, and thus obtain the equivalent analog circuit of the mechanical system, to describe problems of the mechanical resonance system with the equivalent analog circuit.

Currently traditional resonance demodulation method widely uses band-pass filter to extract fault frequency components and uses electronic resonator to extract fault frequency components based on electronic resonance demodulation method. For the band-pass filter and the electronic resonator with the center frequency W_0 and the quality factor Q, their transmission functions can be expressed as:

$$H(s)=\frac{s\frac{w_0}{Q}}{s^2+s\frac{w_0}{Q}+w_0^2} \tag{3}$$

The relationship between the center frequency W_0 and the bandwidth B can be expressed as:

$$B=\frac{w_0}{Q} \tag{4}$$

Upon Laplace transform respectively for the mechanical resonance system and the electronic resonance system, the expressions can be obtained in s domain:

$$H_m(s)=\frac{x_o(s)}{x_i(s)}=\frac{1}{\frac{m}{k}\times s^2+\frac{\delta}{k}\times s+1} \tag{5}$$

$$H_p(s)=\frac{v_o(s)}{v_i(s)}=\frac{1}{LC\times s^2+\frac{L}{R}\times \mathrm{s}+1} \tag{6}$$

Provided Hm (f) represents the transmission function of the mechanical system, $H_p(f)$ represents the transmission function of the electronic resonator, *x(t)* represents pure fault shock signal, and *n(t)* represents noise signal. The SNR of the original fault and the SNR of the fault after electronic resonator processing can be expressed as:

$$\rho_2(f)=\frac{\rho_x(f)}{\rho_n(f)}H_m(f)H_p(f) \tag{7}$$

Wherein, $\rho_x(f)$ refers to pure fault signal's power spectral density function, while $\rho_n(f)$ refers to noise's power spectral density function.

From the above equation, it can be observed that the SNR passing through the mechanical system and the electronic resonator is $H_m(f)H_P(f)$ times as much as the original SNR.

Moreover, from the point of view of *s* domain, for the mechanical resonance system or the electronic resonance system, the relationship between system input and output in *s* domain can always be expressed in a second order function, as both systems enjoy equivalence in *s* domain. Therefore, the mechanical vibration system can be replaced with the electronic resonance system for fault signal extraction; meanwhile, the electronic resonance system is also known for small size, low cost and high stability, which is easy to implement digital signal processing, widely used in engineering practice.

1.2. Electronic Resonance Principle

This paper adopts series resonance [12-14] system as the electronic resonance system for analysis.

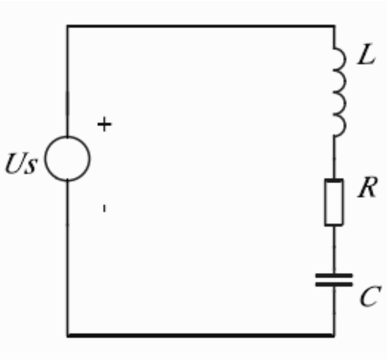

Fig. (3). Series resonance system.

The basic series resonance circuit is shown in Fig. (**3**). The loop equation can be expressed as:

$$I=\frac{U_s}{Z_s}=\frac{U_s}{r+j\left(wL-\frac{1}{wC}\right)} \tag{8}$$

When w satisfies $w_0=1/LC^{1/2}$, the circuit resonates. The main function of the resonance circuit is frequency-selection, the frequency of signal U_s is variable, while inductive reactance jwL and capacitative reactance 1/jwC are also variable. As frequency f increases, inductive reactance increases, while capacitive reactance decreases. When the applied signal frequency is equal to w_0, the inductive reactance in the circuit is equal to the capacitive reactance, the circuit is under pure resistance state, and at this time, the current is maximum and resonance occurs; when the applied signal frequency is away from the resonance frequency, the circuit reactance becomes larger, and the larger the detuning, the smaller the loop current, so as to play the function of frequency-selection.

1.3. Resonance Demodulation Based on Electronic Resonance

Due to the equivalence between the electronic resonance system and the mechanical resonance system, the introduction of resonance to traditional resonance demodulation method contributes to the resonance demodulation method based on electronic resonance, as shown in Fig. (**4**).

(1) Electronic resonance gain: broadband fault signal is greatly strengthened at the acceleration sensor resonance frequency, and this high-frequency inherent vibration is separated through the resonator whose center frequency is equal to this inherent frequency.

(2) Envelope detection: a pulse train consistent with fault impact frequency is acquired upon envelope detection for the resonance signal through band-pass filter.

(3) Low-pass filtering: signal after envelope detection can remove residual high-frequency interference noise and retain low-frequency fault signal components through low-pass filter.

(4) Spectral analysis: power spectrum calculation is carried out, fault points from the power spectrum chart are analyzed, and compared with computed bearing fault feature frequency to judge the specific cause of bearing fault.

2. SIMULATION ANALYSIS

The simulation model adopts rolling bearing inner race pitting fault model [7, 8]:

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

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

f_n refers to oscillation attenuation signal of oscillation frequency.

Setting system sampling frequency F_s=51200 Hz, rotating frequency f_r=7 Hz, inner ring passing through frequency f_i=67, Hzsystem inherent frequency f_n=5900 Hz, constant A_0=1, C_A=1, Φ_A=0 and Φ_w=0. Simulation fault

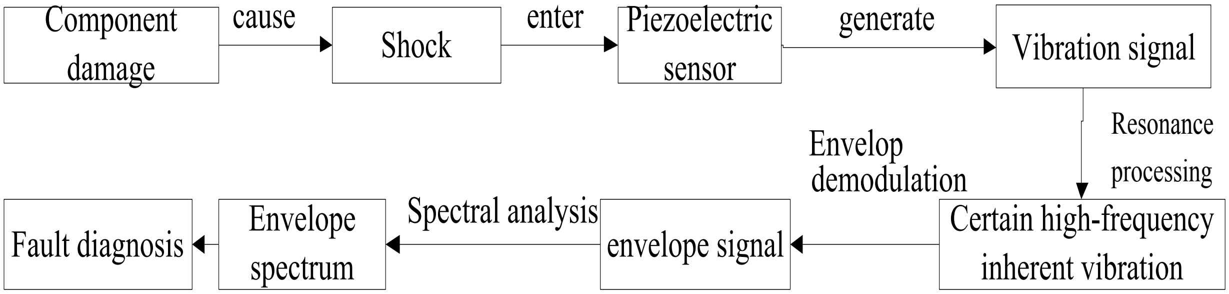

Fig. (4). Resonance demodulation method based on electronic resonance.

signal and its spectrum are shown in Figs. (**5**, **6**) respectively.

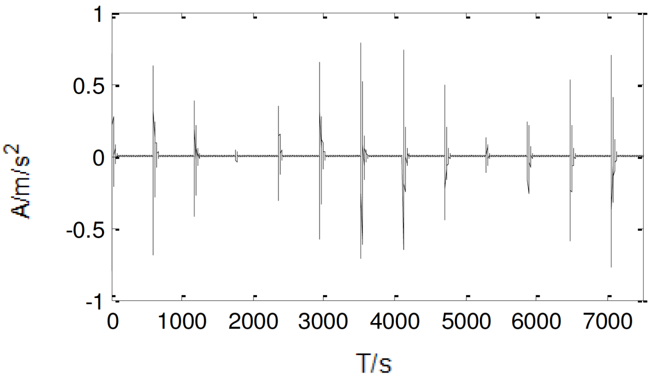

Fig. (5). Simulation fault signal.

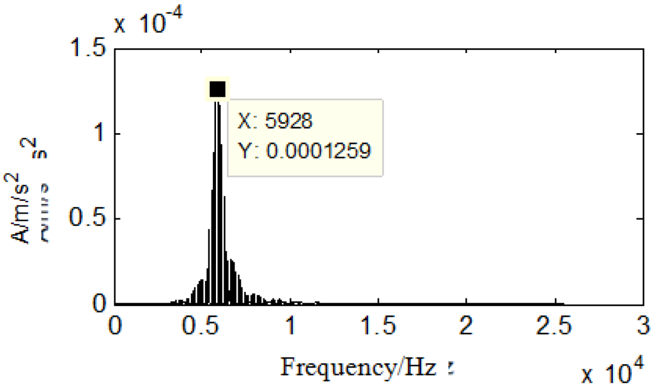

Fig. (6). Simulation fault signal spectrum.

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

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

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

$$H(jw) = \frac{a_1 \times jw}{b_1 \times (jw)^2 + b_2 \times jw + b_3} \tag{11}$$

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 shown in Figs. (**7**, **8**) respectively.

Finally, a spectrum after resonance demodulation is acquired upon envelope demodulation for the signal after resonance processing, as shown in Fig. (**9**).

From Fig. (**6**), it can be observed that for the fault signal within certain bandwidth range with 5.9 KHz as the center frequency, the resonator has carried out 1 KHz bandwidth frequency-selection processing and acquired a signal as shown in Fig. (**8**). In Fig. (**9**), in the spectrum after envelope demodulation, 87 Hz fault frequency and its second and third harmonic frequency components can be analyzed obviously.

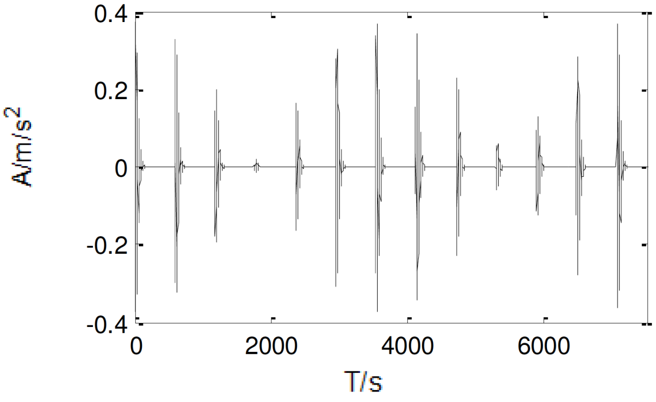

Fig. (7). Fault signal in resonance processing.

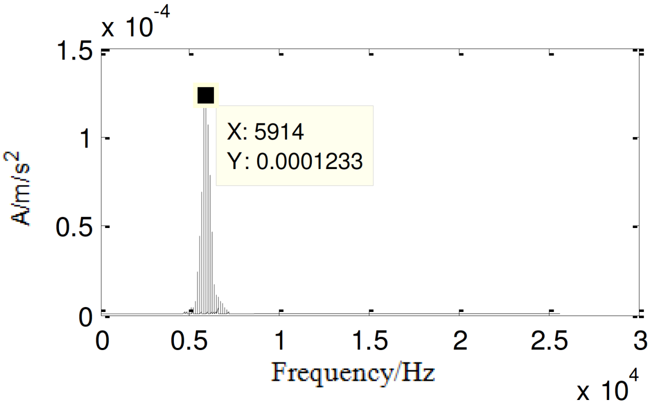

Fig. (8). Fault signal spectrum after resonance processing.

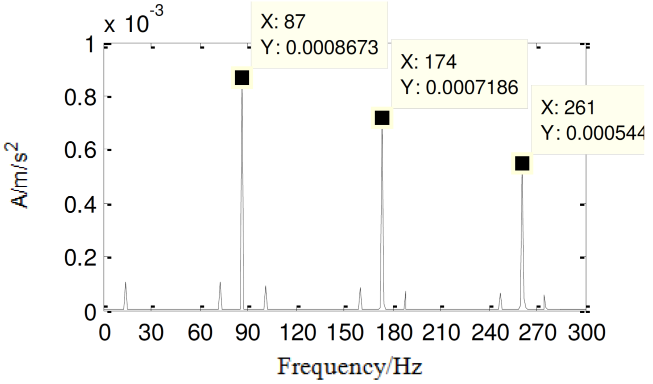

Fig. (9). Fault signal spectrum after envelope demodulation.

To verify the effectiveness of the algorithm, fault signal SNR can be reduced, taking SNR= -30 dB. At this time, the time-domain signal submerged in strong noise and its spectrum respectively can be obtained as shown in Fig. (**10**) and Fig. (**11**). The time-domain signal after resonance processing and its spectrum are respectively shown in Fig. (**12**) and Fig. (**13**).

The signal spectrum after envelope demodulation is shown in Fig. (**14**), from which the fault frequency can be clearly observed, mainly due to the improvement of SNR through resonant gain processing. At a low SNR, the resonance demodulation algorithm based on electronic resonance can still achieve a satisfactory result. Fig. (**15**) shows the processing results with traditional resonance

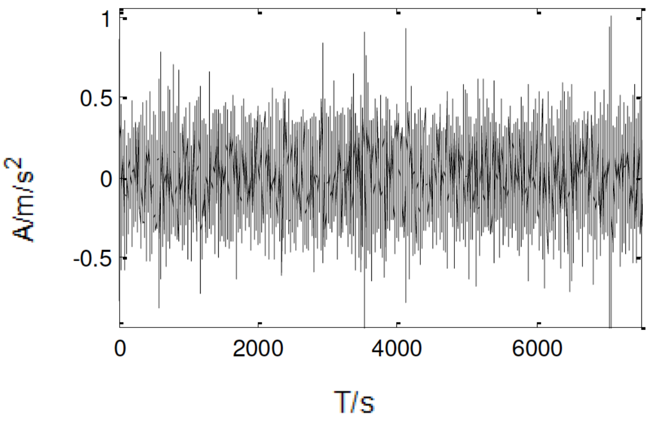

Fig. (10). Fault signal with noise.

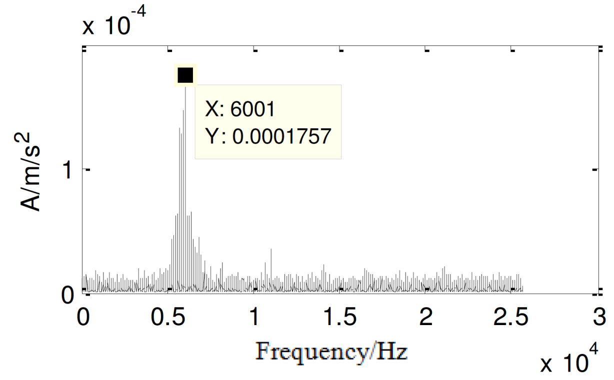

Fig. (11). Fault signal spectrum with noise.

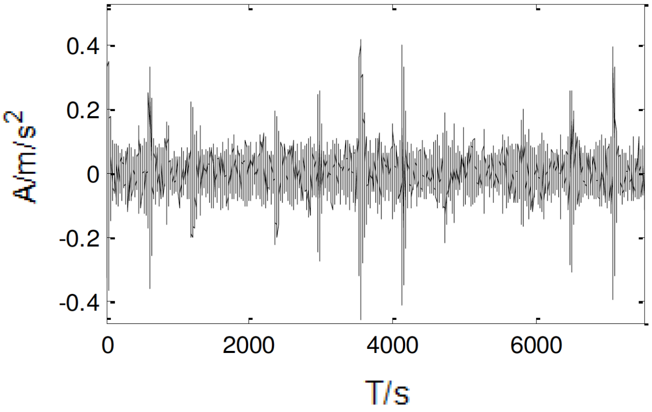

Fig. (12). Fault signal with noise after resonance processing.

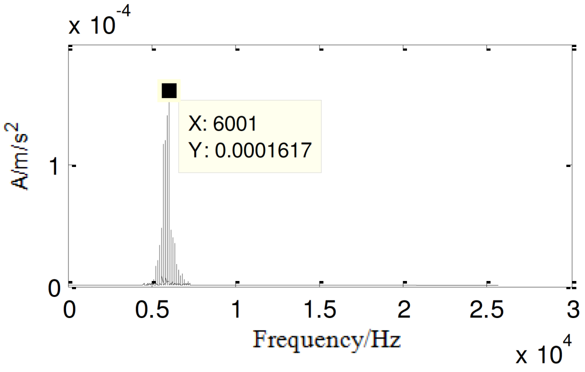

Fig. (13). Fault signal spectrum with noise after resonance processing.

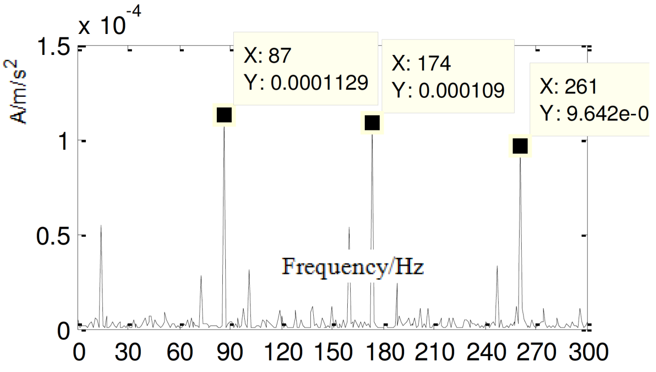

Fig. (14). Fault signal spectrum after envelope demodulation with improved method.

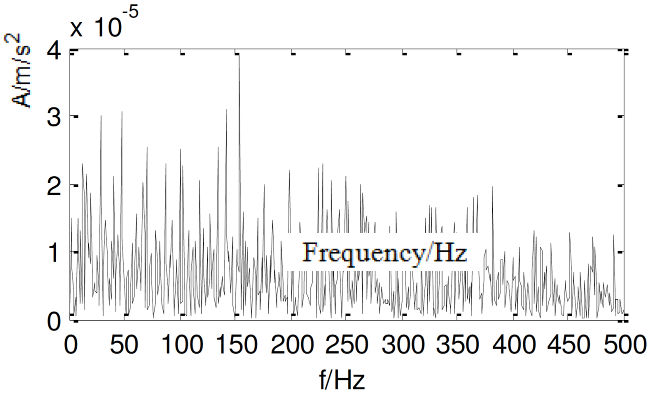

Fig. (15). Fault signal spectrum after envelope demodulation with traditional method.

demodulation method. In contrast, it can be seen that traditional method cannot effectively process early weak fault shock signal under strong noise, for which the effectiveness of this method is verified.

3. EXPERIMENTAL VERIFICATION

3.1. Experimental Wheel Set and Rolling Bearing

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 transmission model adopts friction wheel transmission and hydraulic control system, and utilizes rubber wheel to drive tested wheel set for running-in. The test bench's structure photo and schematic diagram are shown in Fig. (**16**). 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 is provided by National Instruments (NI) Ltd., mainly including NI PXIe-1082 backplane, NI PXIe-8108 embedded controller and NI PXIe-4496 high-precision data acquisition module, the sampling frequency is 51200, and the sampling length is 10s. Sensor arrangement is shown in Fig. (**17**).

Fig. (16). Wagon wheel set rolling bearing fault diagnosis test bench.

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 shown in Tables **1** and **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

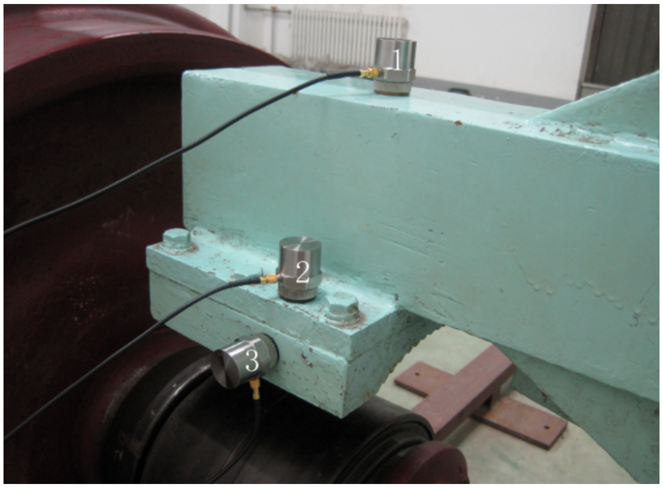

Fig. (17). Sensor arrangement.

Sensor adopts CA-YD-189 piezoelectric acceleration sensor (IEPE), whose installed resonance frequency is identified as 5.9 KHz after frequency sweeping test, and the frequency feature curve are as shown in Fig. (**18**).

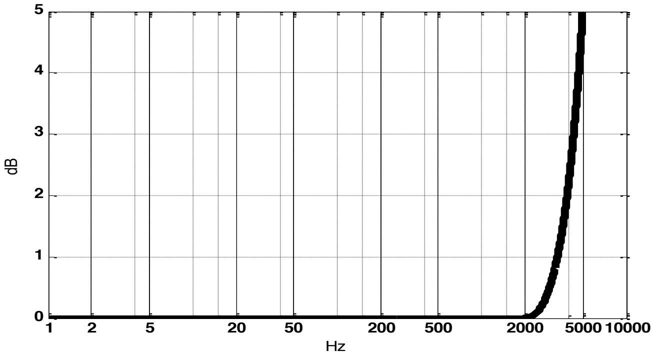

Fig. (18). Sensor typical frequency response curve.

3.2. Analysis of Experimental Results

The bearing fault time-domain signal collected with piezoelectric sensor and its spectrum are shown in Fig. (**19**) and Fig. (**20**). The time-domain signal acquired through resonance demodulation processing with resonance method and its spectrum are shown in Figs. (**21**, **22**). The envelope analysis on demodulated signal is shown in Fig. (**23**) and the signal spectrum after envelope analysis with traditional resonance demodulation method is shown in Fig. (**24**). Resonator's resonation frequency is 5.9 KHz, and the bandwidth is 1 KHz.

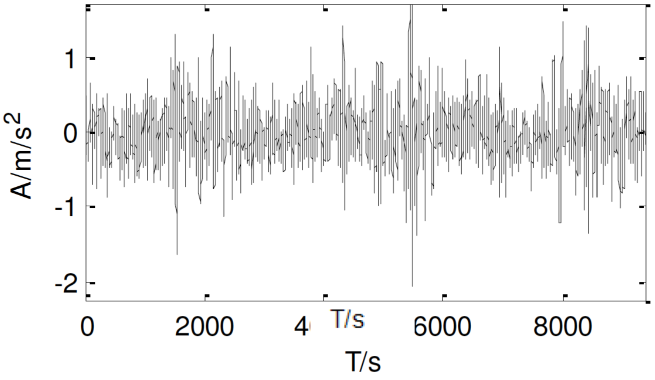

Fig. (19). Original bearing fault time-domain signal.

Figs. (**19**, **20**) respectively show sensor original output signal and its frequency spectrum. As shown in the figure, resonance frequency and its harmonic components can be clearly observed, and upon envelope analysis on this signal, it is hard to distinguish fault feature frequency 87.9 Hz. Figs. (**21**, **22**) respectively show the signal and its frequency spectrum after resonance processing. The signal separated from 1 KHz bandwidth near the resonance frequency after envelope analysis is shown in Fig. (**23**). From the figure, it can be observed that the feature of inner ring fault feature frequency 87.9 Hz and its frequency multiplication 176 Hz and 264 Hz are very obvious. Fig. (**24**) shows the frequency spectrum after envelope analysis with traditional resonance demodulation method. By contrast, it can be seen that in the traditional resonance demodulation method shown in Fig. (**24**), transit frequency (7 Hz) and its harmonic wave at each order still exit, processed SNR is relatively low, causing certain interference to the extraction of fault feature frequency with a direct impact on bearing early fault diagnosis accuracy. By comparing experimental data, it is proved that this method has effectively improved signal SNR and enhanced signal robustness. Therefore, the effectiveness and feasibility of resonance demodulation method based on electronic resonance method can be verified.

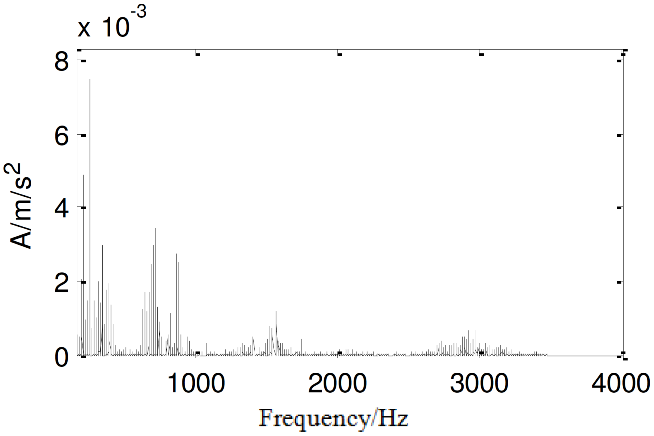

Fig. (20). Original bearing fault signal spectrum.

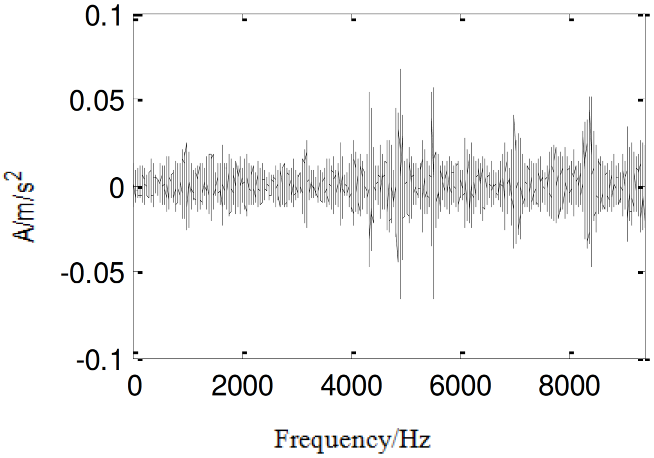

Fig. (21). Fault time-domain signal after resonation gain.

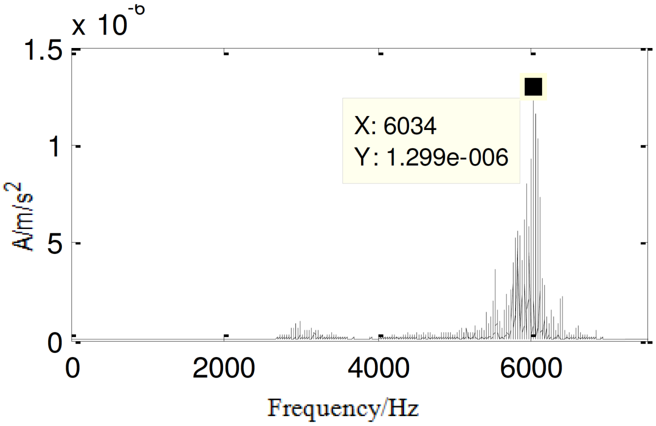

Fig. (22). Fault signal spectrum after resonation gain.

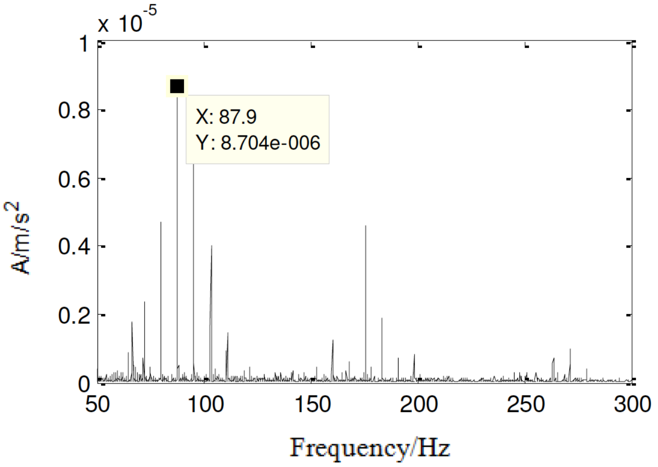

Fig. (23). Signal spectrum after envelope analysis with improved resonance demodulation method.

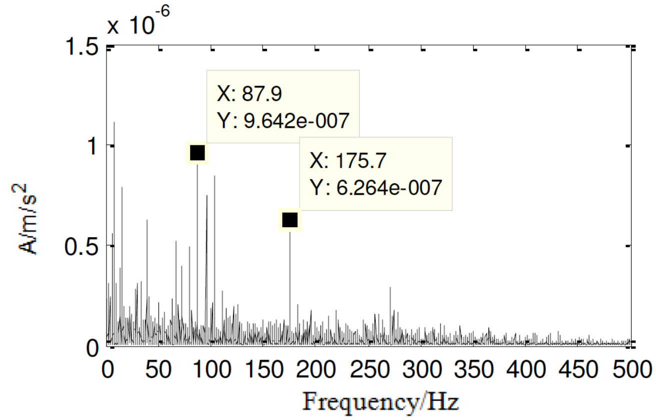

Fig. (24). Signal spectrum after envelope analysis with traditional resonance demodulation method.

CONCLUSION

This paper researched on the application of resonance demodulation technology in wagon rolling bearing early fault feature extraction based on electronic resonance. Compared with traditional resonance demodulation method, this method is known for simple operation and high reliability, which, through resonation gain for sensor output signal with electronic resonator, has defects of traditional resonance demodulation method, achieving ultra-narrowband high resolution detection, and improving fault feature signal SNR. Especially for rolling bearing early fault and low SNR environment, the application of traditional resonance demodulation method is very difficult for fault feature extraction, but the application of resonance demodulation method based on electronic resonance can accurately judge such fault. Meanwhile, as bearing early weak fault signal frequency components are complex, it is hard to judge if there is any fault solely due to traditional resonance demodulation with sensor signal. However, the organic combination of fault signal through sensor and electronic resonator can demodulate early fault feature frequency well. When the center frequency of electronic resonator is equal to the resonance frequency of the mechanical system, it is, in fact, equivalent to twice of high-frequency resonance, and in this way, the SNR is doubled, enhancing signal robustness; meanwhile, the electronic resonator may collect high-frequency vibration signal caused by weak fault impact to the center frequency of resonator for amplification so the effects are more prominent in demodulation of bearing early weak fault signal.

Finally, the method is verified through simulated fault bearing signal and actually collected fault signal. The results prove the correctness and effectiveness of the method used in this paper having an important guiding significance for engineering practice.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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