Gearbox Fault Diagnosis Based on EEMD-SVD

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Abstract
Gearbox is an important mechanical device to transmit power. In order to ensure the normal operation of gearbox under the condition of top load, high efficiency and high precision, it's necessary to extract fault feature information using signal processing method and to further analyze and research gearbox fault. In the paper an improved de-noising method based on de-noising of singular value decomposition (SVD) is proposed, which sets threshold on the basis of standard derivation of the difference between adjacent singular values, and simulation is made. Through further research, combined it with ensemble empirical mode decomposition (EEMD), a new de-noising method based on EEMD-SVD (ensemble empirical mode decomposition and singular value decomposition) is derived, which is proved to be an effective de-noising method through simulation experiment. EEMD-SVD method is applied to fault diagnosis of gearbox and good results are achieved.

Key words: SINGULAR VALUE DECOMPOSITION, EEMD-SVD, GEARBOX, FAULT DIAGNOSIS

Introduction

Gearbox is an important mechanical power transmission device, mainly composed of gear, shaft, bearing, housing and other components. In order to ensure the normal operation of gear box under the condition of top load, high efficiency and high precision, the analysis and study of gearbox fault becomes very important. Extracting the fault feature information is the key of gearbox fault diagnosis, and the conventional method of fault feature extraction is signal processing. Gearbox vibration signal is complex and presents the non-stationary characteristics. The machine is running with a lot of noise, coupled with acquisition instrument and the surrounding environment and other influence factors, thus the observed by the sensor to the vibration signal inevitable in the presence of random noise. When the observation signal mixed with noise, the signal resulting from the separation also contains noise. When the noise is bigger, the weak fault signal characteristics are likely to be submerged and also it is very difficult to extract fault feature;

moreover, larger noise can cause separation algorithm separation failed and cannot get the right result. As a result, to reduce the noise of observed vibration signal or the separated vibration signal is very necessary [1].

With the deepening of the research of the vibration signal processing technology, new signal processing methods have increasingly been put forward, and have been applied to gearbox fault diagnosis. The commonly methods used by experts at home and abroad in the research of gearbox fault diagnosis are Hilbert Huang transform, BP neural network, empirical mode decomposition, ensemble empirical mode decomposition, singular value decomposition, etc. But a single method has limitations [2]. So the experts decided to combine two kinds of methods to study of gearbox fault diagnosis. Li Rong put forward a method of compound fault diagnosis of gearbox based on CPP and EEMD [3]. Ma Baixue diagnosed gearbox fault on the basis of EEMD and two-dimensional marginal spectrum entropy [4]. Hou Gaoyan applied adaptive morphology which is based on EEMD in gear fault diagnosis [5]. You Ziyue adopted BP neural network and EEMD in the fan gear box fault diagnosis [6]. Zhu Yu studied the fault diagnosis of the gearbox fault based on wavelet de-noising and EMD and got some results [7]. Zhangxiang has carried on the optimized MP algorithm and EEMD in the gearbox fault diagnosis research [8]. Mitchell Yuwonoa proposed an automatic bearing defect diagnosis method based on swarm rapid centroid estimation (SRCE) and hidden markov model (HMM) [9].

In this paper, we put forward an improved method according to the standard derivation of adjacent singular value difference to set threshold on the basis of singular value decomposition and put into simulation analysis. Then through further research, combined it with EEMD decomposition, we got EEMD-SVD, which turns out to be an effective de-noising method through simulation experiment. EEMD-SVD method is applied to fault diagnosis of gear box, first to make the signal de-noised with EEMD-SVD, and then to analyze its frequency domain characteristics, finally to judge it. Promising results have been achieved.

The improved SVD algorithm

In general, it is considered that the random noise is the white noise of the Gauss distribution. Gaussian white noise spectrum density is a constant, but the useful signal spectrum is usually not a constant and concentrates on the low frequency part. According to this characteristic, we can use different time-frequency analysis methods for noise reduction. In this paper, based on the singular value decomposition (SVD), an improved method is proposed, which preserves the singular values according to the standard deviation of the difference between the adjacent singular values.

For any observation signal x(t), by the phase space reconstruction theory, structure matrix A can be constructed according to signal x(t) as follows [10].

$$A=\begin{bmatrix} x(1) & x(2) & \cdots & x(N-L+1) \\ x(2) & x(3) & \cdots & x(N-L+2) \\ \vdots & \vdots & \vdots & \vdots \\ x(L) & x(L+1) & \cdots & x(N) \end{bmatrix} \quad (1)$$

While N is the length of the signal, L is the dimension of the reconstruction matrix and $1 < L < N$

By singular value decomposition of formula (1), it can receive a set of singular value greater than zero. If the signal is noise signal, then the decomposed singular value is small and the adjacent singular value difference is very small; if the signal is useful signal, then the decomposed singular value is relatively large [11]. For signals composed of noise and useful signal, the larger values of the singular values correspond to the useful signal, while the noise is mainly represented by the smaller singular values. So we can use appropriate methods to extract the larger singular values, then the reserved singular values and its corresponding orthogonal matrix constitute the reconstruction matrix, and by further processing of the reconstructed matrix, it can eliminate the noise in the original signal. At present, people often use singular value curve, SNR experience, and increment of singular entropy to determine the number of singular values, but these methods cannot clearly give the effective order, mainly on the basis of experience to select [12-13]. This paper, based on the research of the singular value of the containing noise signal, puts forward a method, which take standard deviation of difference sequence of adjacent singular value as a threshold to determine the number of singular value, and this method can effectively keep the number of singular values is determined.

Take the original signal $x(t)=2\sin(50\pi t)+\cos(100\pi t)$, mixed with white noise. The signal to noise ratio of the mixed signal is 0 db. Singular value decomposition of the signal to noise reduction, the result is shown in figure 1, by the calculation, the cross correlation coefficient between the original signal and the signal after noise reduction is 0.9978, and the signal to noise ratio is 23.4983.It’s shown that basic noise is eliminated and the noise reduction effect is good. However, through the repeated simulation experiment, we find if the useful signal is completely submerged by noise, the noise reduction effect is not ideal.

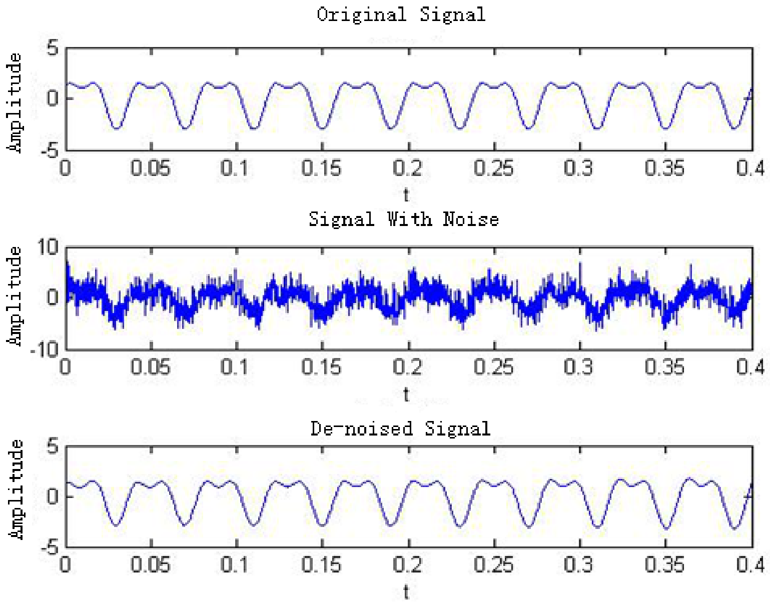

Figure 1. De-noised method based on SVD

EEMD-SVD noise reduction

For noise reduction method of the above, when there is a big difference between the signal components in the original signal, small amplitude signal is not easy to be extracted and easy to be discarded, resulting in the loss of signal characteristic components. Therefore, on the basis of the EEMD decomposition, combined with the improved SVD noise reduction method, we put forward the EEMD combined with SVD method for noise reduction.

The sensor observation signal by Ensemble Empirical Mode Decomposition can get each order IMF components and a remainder, the low order IMF frequency is high and the characteristic time scale is small, while the high order IMF frequency is low, the characteristic time scale is big [11]. The observed signal is often mixed with random noise, generally, the noise has a greater effect on the low order IMF component, and the higher order IMF has little effect. The decomposed IMF is screened, which can remove the false IMF component, and the retain IMF component to be noise reduction processing, then reconstruct signal can achieve the purpose of noise reduction. Through singular value decomposition for each IMF, we can get the corresponding singular eigenvalues. Analysis of these eigenvalues indicated that when the IMF component contained the original signal characteristic component, its mean square deviation of adjacent singular value difference is big, while the false IMF component corresponding singular value difference mean square error is small. Therefore, according to the characteristics we can screening the IMF component and reduce the IMF component noise. After the signal is decomposed by EEMD, the signal is decomposed into IMF components which contain different frequency components and the noise, which is conducive to the extraction of weak signal.

The proposed EEMD-SVD decomposition and noise reduction process is as follows:

(1) Ensemble Empirical Mode Decomposition of the original signal x(t), we can get K IMF components and a residual component .

(2) Singular Value Decomposition of each IMF component, we get the corresponding singular value and mean square deviation of the difference of adjacent singular value sequence.

(3) To sort the mean square deviation from big to small, calculate the cumulative frequency and according to the cumulative frequency screening the IMF component. The cumulative frequency threshold is from 85% to 90%.

(4) To make the IMF component for noise reduction processing, and then adding together, the signal after the noise reduction is obtained.

Experimental Verification

In order to verify that EEMD-SVD is an efficient method to reduce noise, we take the following signals and mixed with noises to simulate.

$$x_1(t) = 5\sin(1100\pi t + 2t) + 0.5\sin(2200\pi t + 5t) + 3t\sin(3300\pi t + t) \tag{2}$$

$$x_2(t) = (1 + \sin(50\pi t))\sin(280\pi t) + 0.5(1 + 1.5\cos(50\pi t))\cos(490\pi t) \tag{3}$$

$$x(t) = x_1(t) + x_2(t) + n(t) \tag{4}$$

Where n(t) is noise. The signal to noise ratio of mixed signal is 0db.Then respectively use adaptive wavelet soft threshold method and EEMD-SVD to reduce noise. De-noised waveform can be seen in

Fig.2.Compared with four time domain waveform in Fig.2, we can see that the signal amplitude is declined and some of the noise is eliminated after the noise reduction. But it is still unknown whether the two methods improve the signal to noise ratio.

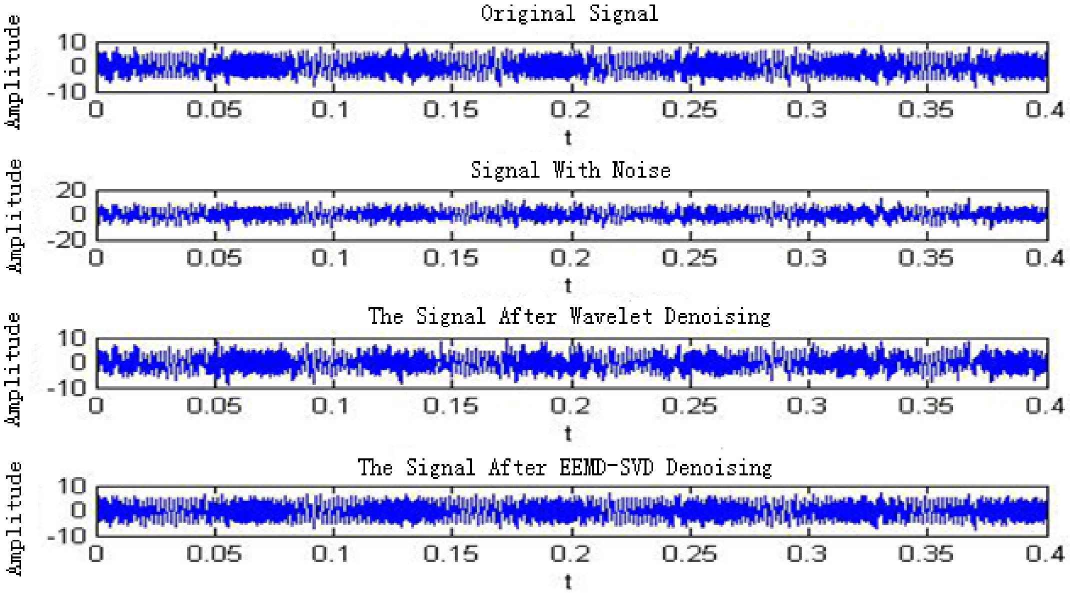

Figure 2. Time domain waveform of de-noised signal

By the calculation, after wavelet de-noising, the signal to noise ratio is 7.7970, and the cross correlation coefficient between the de-noised signal and the original signal is 0.9164. While after EEMD-SVD de-noising, the signal to noise ratio is 14.5880, and the cross correlation coefficient is 0.9828. The de-noised signal is similar to the original signal by two noise reduction methods. However, it is hard to find whether the frequency characteristics of the original signal are lost after the noise reduction from time domain waveform. Make amplitude spectrum of the de-noised signal by Fourier transform and show in Fig.3.

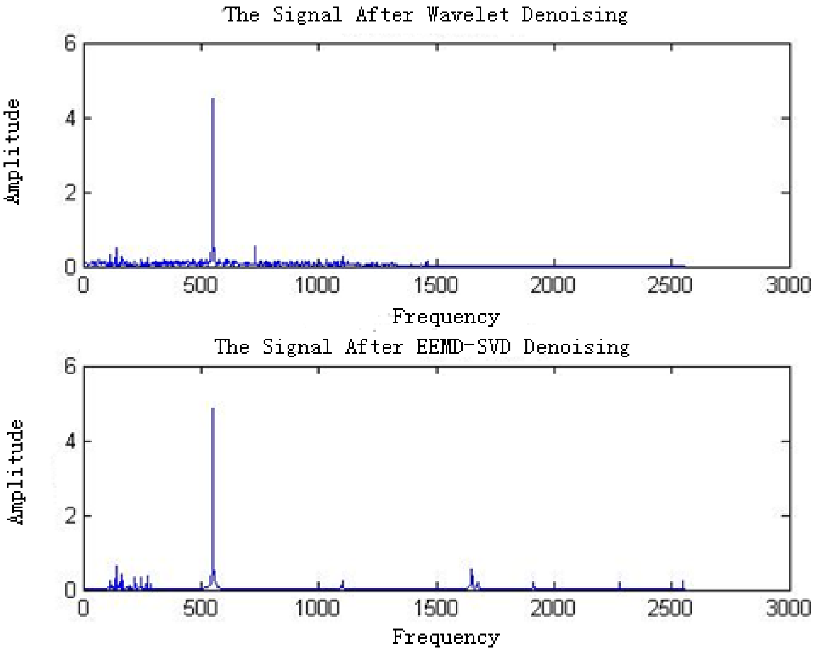

Figure 3. Amplitude spectrum of the de-noised signal

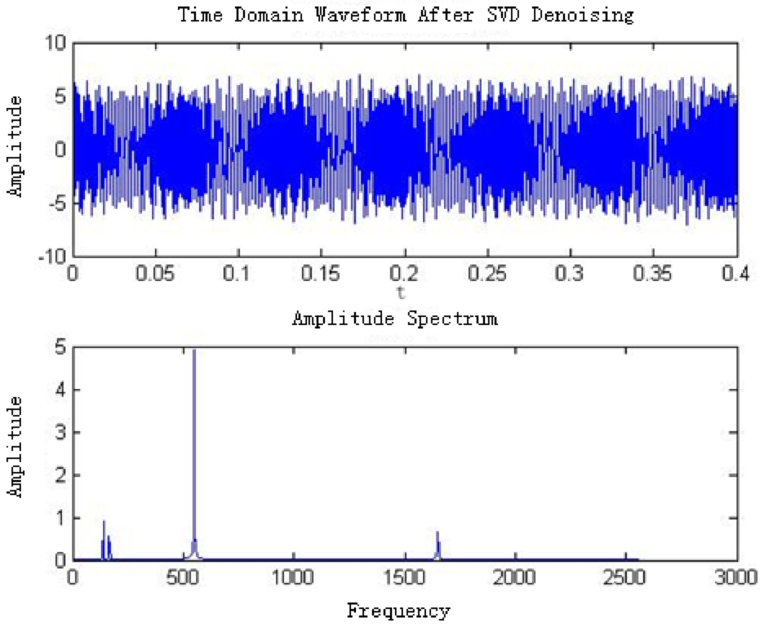

Figure 4. The de-noised signal based on improved SVD

Compared with the original signal, it can be seen that the signal still contains many noise frequency components after wavelet de-noising from Fig.3. The frequency of 1100Hz of the original signal is almost drowned by the noise. Moreover, the component of the original signal frequency of 1650Hz is lost. However, the signal retains all the frequency components of the original signal after EEMD-SVD de-noising, furthermore, most of the noise is eliminated and only a small amount of noise component is retained. Therefore, EEMD-SVD de-noising is better than the wavelet de-noising.

Fig. 4 is the time domain waveform and amplitude spectrum after de-noising by using the improved SVD method. The signal to noise ratio of the de-noised signal is 11.9010, and the cross correlation between the de-noised signal and the original signal is 0.9772. As can be seen from Fig. 4 the amplitude spectrum, after SVD de-noising ,signal retaining the original signal frequency is 140Hz, 145Hz, 550Hz and 1650Hz components, other components are lost. After many times of simulation, we found this is because the original signal have a big magnitude difference of frequency components and mixed with the strong noise signal, resulting in small value of the weak signal almost submerged by noise, when containing noise signal to noise ratio than high (this experiment is 7db), the missing ingredient can be re-extracted.

Through the simulation experiment, we can find that EEMD-SVD method has better adaptability and good noise reduction effect; When the noise is small, the wavelet de-noising, the SVD de-noising, the EEMD-SVD de-noising can achieve good results, however, when the noise is large and the original signal contains small amplitude weak signal, the noise reduction effect of EEMD-SVD is better than that of wavelet de-noising and SVD; When the noise signal is completely submerged the useful signal, the above three methods cannot extract the useful signal ,which means the methods are invalid.

Fault diagnosis example

Gearbox experiment platform is the secondary speed reduction gearbox system. Through replacing intermediate shaft pinion, we can set the working condition of the gearbox system, for example broken teeth fault of gear, gear eccentricity fault, roots of gear crack fault, etc. Some of the fault gears and bearings are shown in figure 5.

(a)Root crack fault (b)Edentulous fault (c)Bearing inner ring fault (d)Rolling element fault

Figure 5. Part of the fault gear and bearing

Gearbox transmission ratio is 8.625, and its internal structure diagram shown in Fig.6. The transmission ratio of the input shaft and the intermediate shaft is 3.45, the number of gear teeth is respectively 29 (1st gear), 100 (2nd gear); the transmission ratio of the intermediate shaft and the output shaft is 2.5, the number of gear teeth is respectively 36 (3rd gear), 90 (4th gear).

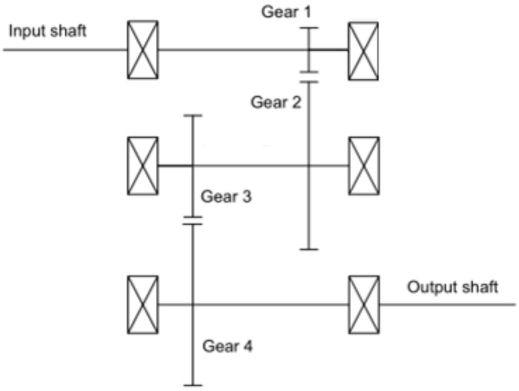

Figure 6. Schematic diagram of the internal gear box

The vibration signal of the gearbox used in the analysis is acquired by the HG-8916 synthetic data acquisition fault diagnosis system. The data acquisition module of the system is developed by LabVIEW, and 8 vibration signal acquisition channels and 4 speed channels can be collected at the same time , which can be acquired by time domain bar graph, time domain, average time domain, average frequency domain, etc. When signal time domain sampling, the maximum sampling number is 32768 and the maximum analysis frequency is 50KHz.The parameters are set up according to the requirement when the data is collected. Due to the constraints, gearbox cannot be disassembled, data acquisition sensor is installed on the box body near the bearing position, measuring point layout diagram as shown in Figure 7.

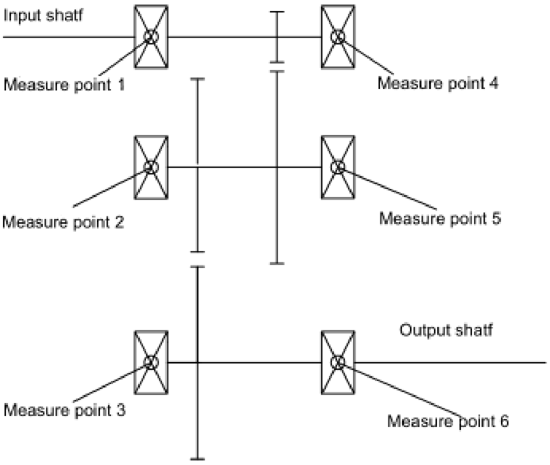

Figure 7. Arrangement diagram of measuring point

A normal gear in the intermediate shaft will be replaced with a fault gear with root crack, which makes the gearbox in gear partial abnormal fault state, then setting the sampling frequency of 5120Hz, the sampling points of 4096 and the actual motor rotation frequency of 17.5Hz. By calculated, the Rotational frequency of the intermediate shaft is 5.10Hz and the Rotational frequency of the output shaft is 129.1Hz, the input shaft and the intermediate shaft gear meshing frequency is 516.2Hzand the intermediate shaft and the output shaft meshing frequency is 186.3Hz. The vibration signal of the gearbox is acquired by the time domain waveform of the signal in Fig.8.

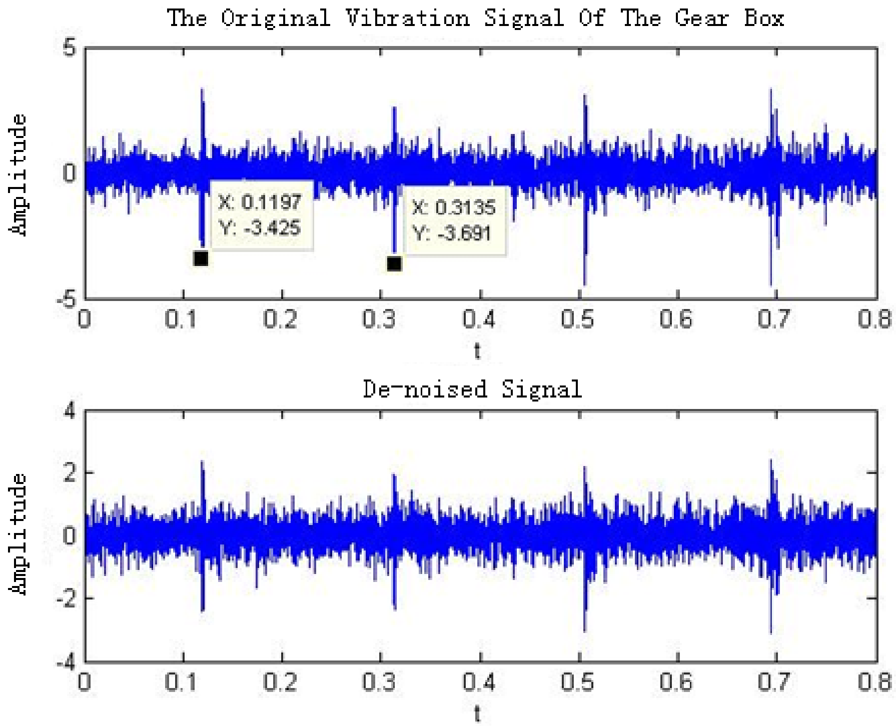

Figure 8. Time domain waveform of signal

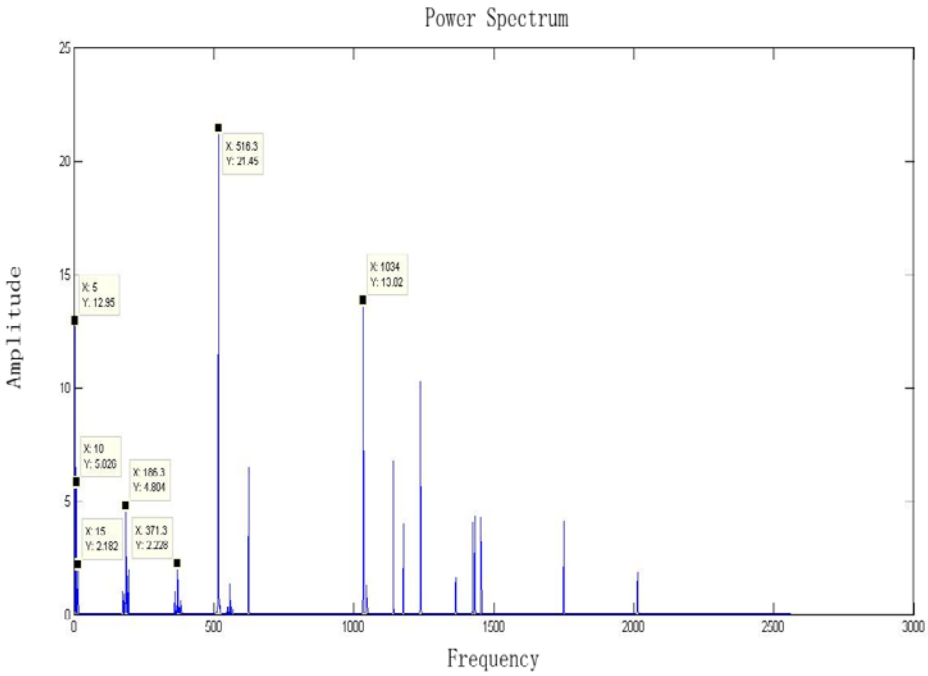

Figure 9. Power spectrum of denoised signal

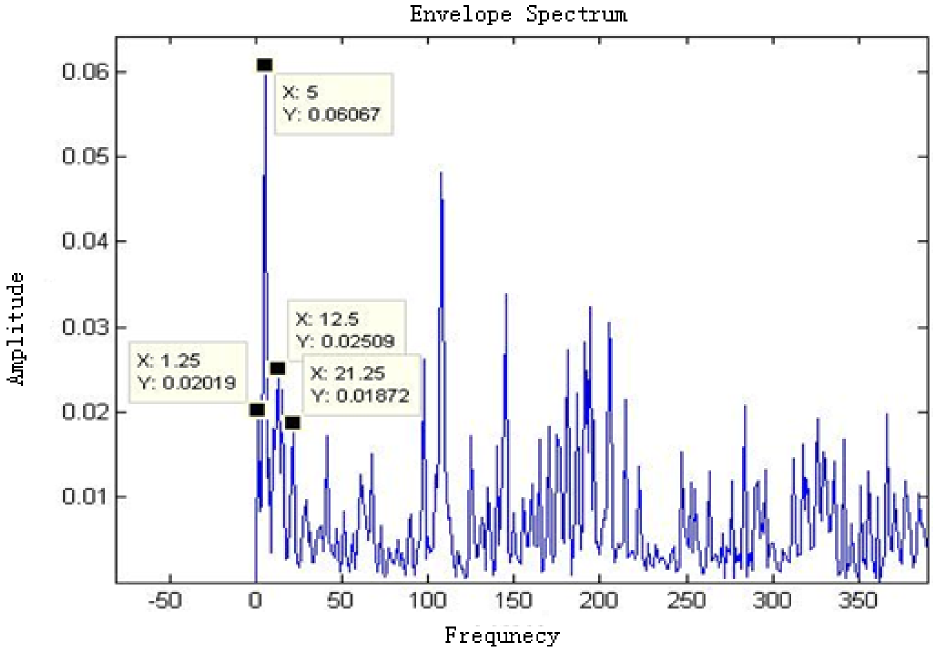

Figure 10. Envelope spectrum of de-noised signal

EEMD-SVD is used to de-noise the collected signal. The signal waveform after de-noising is shown in Fig. 7. Kurtosis index is calculated to be 6.24, and the peak index is 10.83, power spectrum as shown in Fig. 8. From figure 8, it can be seen that there are obvious periodic shocks in the time domain, which can be deduced from the presence of the gearbox with the impact of the characteristics of the fault and the impact frequency is about 5.16Hz, approximately equal to the middle frequency. From Figure 9, we can see that in the vicinity of the 186.3Hz, and 557.5Hz 371.3Hz have obvious wave crest and band edge, after thinning found side bands spaced to 5Hz. The three frequencies are the intermediate shaft and the output shaft gear meshing frequency and its frequency multiplication. At the same time, power spectrum in 5Hz, 10Hz and 15Hz also has distinct peaks, which is almost equal to the intermediate shaft rotation frequency and the 2, 3 doubling. In addition, through the de-noised signal envelope spectrum analysis, we can demodulate the intermediate shaft rotational frequency and its doubling, the refinement of the envelope spectrum as shown in Figure 10. From the figure we can also observe the intermediate frequency, the output shaft rotational frequency, and their combined frequency doubling. It is suggested that the signal exists in middle frequency and output shaft rotational frequency for signal modulation wave. In summary, it can be determined that the intermediate shaft in the gearbox for small gear tooth number 36 (3rd gear) exists local abnormal fault.

Conclusions

(1)The method of EEMD-SVD de-noising has better adaptability and good de-noising effect. When the noise is small, the wavelet de-noising, the singular value de-noising, EEMD-SVD de-noising can achieve good effect, when the noise is large and the original signal contains small amplitude weak signal, he noise reduction effect of EEMD-SVD is better than that of wavelet de-noising and SVD; however, when the noise signal completely submerged the useful signal, the above three methods cannot extract the useful signal, which means the methods are invalid.

(2)When EEMD-SVD method is applied in gearbox fault detection, through the analysis of the gearbox root crack fault we can find that gearbox vibration signal doesn't lost the useful components, while highlight the fault characteristic frequency after de-noised by EEMD-SVD, which is convenient to go further analysis, then to make right judgment on fault types.

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