Early Weak Fault Diagnosis of Gearbox Based on ELMD and Singular Value Decomposition

Chaoge Wang
School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China
E-mail: dutwcg@163.com

Hongkun Li
School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China
E-mail: lihk@dlut.edu.cn

Jiayu Ou
School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China
E-mail: Ojy950425@mail.dlut.edu.cn

Gangjin Huang
School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China
E-mail: huanggj@mail.dlut.edu.cn

***Abstract*—As important transmission device in the entire mechanical system, gearboxes shoulder the responsible for transmitting motion and torque. Gearboxes early fault diagnosis technology can realize early warning of fault, improve the reliability of equipment operation, and avoid major accidents. However, the background noise of the gearbox early fault vibration signal is strong, and the weak fault features are often submerged and the feature information is difficult to extract. Aiming at these problems, a new early fault diagnosis method by combining ensemble local mean decomposition (ELMD) and singular value decomposition (SVD) is proposed. Firstly, the raw gearbox fault vibration signal is broken down into a large number of narrow-band product functions (PF) with the ELMD method. Then, the PF component containing the most abundant fault characteristics is selected as the sensitive feature to be analyzed. The SVD is applied to the sensitive PF component, and the singular value difference spectrum is obtained. The reconstructed signal order is determined in the singular value difference spectrum. Finally, the Hilbert envelope demodulation analysis is performed on the signal which is reconstructed, and the fault feature information in the envelope spectrum is extracted. By comparing with the theoretical value, the fault location of gearbox is determined. The effectiveness and superiority of the proposed method are verified by the actual fault data of the gearbox.**

Keywords-ensemble local mean decomposition; singular value difference spectrum; gearbox; feature extraction; fault diagnosis

I. INTRODUCTION

Gearbox is an important transmission device for rotating machinery, which plays a key link role in the whole mechanical system and shoulders the responsibility of transmitting motion and torque. Usually gearbox work in harsh environment such as high speed, heavy load and strong impact, which easily causes local faults such as wear, fracture, abrasion and pitting of gear in gearbox [1,2]. When the gearbox fails, it will cause mechanical transmission failure and economic loss. In severe cases, the whole system will be paralyzed or disastrous consequences. Therefore, gearbox is also the focus of maintenance reliability of aerospace vehicles, nuclear power plants, thermal power plants, heavy vehicles and other large-scale equipment. Gearbox fault diagnosis is a typical problem of non-linear signal processing and weak fault feature information recognition. Consequently, it is important to develop the early fault diagnosis research to effectively control the health status of gearbox and realize effective early warning of catastrophic faults [3].

The local mean decomposition (LMD) method is an adaptive time-frequency analysis method [4], which is especially fit for the processing analysis of non-linear and non-stationary signals. Compared with empirical mode decomposition (EMD) method [5], LMD has many advantages such as fewer iterations and no obvious endpoint effect, thus it has been highly applied in the field of mechanical fault diagnosis. However, LMD has the same serious modal aliasing as EMD method. In order to suppress modal aliasing, Yang et al [6] combined ensemble empirical mode decomposition (EEMD) method [7] with LMD method and proposed ensemble local mean decomposition (ELMD) method. The ELMD method adds different white Gaussian noise to the target signal several times, decomposes the mixed signal by LMD, and calculates the total average of the PF components obtained by multiple decompositions as the final result [8]. White Gaussian noise is automatically eliminated after multiple averages. Using ELMD method to decompose complex multi-component gear fault vibration signals, finite single-component amplitude-modulated frequency-modulated (AF-FM) signals can be obtained, thereby highlighting the local characteristics of the signals [9,10]. However, since the initial fault signal of gearbox is very weak and often drowned by multiple interference sources and noise of mechanical system, it is very hard to collect fault characteristic frequency information from the spectrum of PF component obtained by the ELMD decomposition. Singular value decomposition (SVD) has good de-correlation, and its decomposed singular value can reflect the intrinsic attributes of the data [11,12]. The signal analysis method on account of SVD can realize the reconstruction of the signal, effectively clear up the noise feature in the signal and extract weak fault feature information [13].

According to the above-method analysis, this paper proposed a new diagnostic method based on ELMD-SVD. The

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analysis of the measured gearbox signal proves that the method proposed can accurately and effectively extract the weak feature information hidden in the strong noise in the early stages of failure, which realize the early fault detection and diagnosis of the gearbox.

II. A DESCRIPTION OF THEORETICAL BACKGROUND

A. ELMD Method

Let the original signal be $x(t)$, the essence of LMD algorithm is to decompose $x(t)$ into the sum of finite number of PF components and a residual term $u_m(t)$. The expression is [4]:

$$x(t) = \sum_{i=1}^{m} PF_i(t) + u_m(t) \tag{1}$$

Like EMD, the LMD method usually causes modal aliasing due to intermittent or discontinuous signals [5]. ELMD algorithm adds different amplitude white Gaussian noise to the original signal in order to improve the dispersion interval of extreme points of the signal, and then calculates the mean value of PFs obtained by multiple LMD decomposition to cancel the mixed white noise [6]. This method can not only get the real PF component but also remove the influence of external noise, and finally effectively suppress the mode aliasing phenomenon of LMD. The specific steps of ELMD algorithm are as follows [8-10]:

Step 1: To the original signal $x(t)$, M times of white noise having amplitude of k (k takes 0.01~0.04 times the standard deviation of the signal $x(t)$) and mean value of 0 are added, and then the analyzed signal is obtained, that is:

$$x_m(t) = x(t) + n_m(t) \tag{2}$$

Step 2: LMD decomposition is performed on $x_m(t)$ to obtain N PFs, and $pf_{i,m}(i = 1,2,3,...,N)$ is the m th PF component obtained by decomposing the white noise amplitude after the i th time.

Step 3: If $m \le M$, let $m = m+1$, return to step 2.

Step 4: By calculating the total average of the obtained PFs, it can be obtained that:

$$PF_i = \frac{1}{M}\sum_{m=1}^{M} pf_{i,m}(i=1,2,\dots,N; m= 1,2,\dots M) \tag{3}$$

Step 5: The output PF_i is the i th PF obtained by ELMD, $i = 1,2,3,...,N$.

B. Singular Value Difference Spectrum

Let $Y = (y(1, y(2),..., y(N))$ be a noisy discrete digital signal. According to the phase space reconstruction theory, construct a $m \times n$ order Hankel matrix with signal.

$$H = \begin{bmatrix} y(1) & y(2) & \cdots & y(n) \\ y(2) & y(3) & \cdots & y(n+1) \\ \vdots & \vdots & \vdots & \vdots \\ y(N-n+1) & y(N-n+2) & \cdots & y(N) \end{bmatrix} \tag{4}$$

where, N is the signal length, $1 < n < N$. Let $m = N - n + 1$, and then $H \in R^{m \times n}$. The real matrix H is also named the reconstructed attractor orbit matrix [11].

Matrix H reflects its dynamic characteristics in reconstructed space by reconstructing attractor's characteristics. The SVD decomposition of matrix H can be expressed as follows:

$$H = U \sum V^{\tau} \tag{5}$$

Wher $U = (u_1, u_2,..., u_m) \in R^{m \times n}$, $V = (v_1, v_2,..., v_n) \in R^{m \times n}$ are a set of orthogonal matrix. $\sum = (diag(\delta_1, \delta_2,..., \delta_q), 0)$ or its transposed matrix is depended on $m \le n$ or $m > n$. where $\sum \in R^{m \times n}$, 0 represents zero matrix, $q = \min(m, n)$, and $\delta_1 \ge \delta_2 \ge ... \ge \delta_q \ge 0$ call the singular value of matrix H .

When creating a signal Hankel matrix, the rows number and columns number are required to be as large as possible. Therefore, the structure of the matrix can be determined according to the following principles: When the length N of the signal is equal, the matrix rows number $m = N/2+1$, and the number of columns $n = N/2$. According to the above analysis, $q = \min(m, n)$ can take the maximum value $q = N/2$; when the length N is odd, the matrix rows number $m = (N+1)/2$, and the columns number $n = (N+1)/2$, then q can take the maximum value $q = (N+1)/2$. The Hankel constructed according to this method can achieve better noise reduction after SVD decomposition and reconstruction [12].

Assuming that descending sequence of all singular values is $\delta_i (i = 1,2,..., q)$, then:

$$b_i = \delta_i - \delta_{i+1} \qquad i = 1,2,..., q-1 \tag{6}$$

The serial $B = (b_1, b_2,..., b_{q-1})$ composed of all b_i is named a singular value difference spectrum described the specific transformation of two adjacent singular values. According to the definition of the differential spectrum [13], when two adjacent singular values differ greatly, a notable peak value will be produce in the differential spectrum, and it will unavoidable be a max peak in the whole differential spectroscopy. The appearance of these peaks is due to the irrelevance of noise and useful signals. If the maximum peak of the difference spectrum appears at the sth point, it can achieved the signal reconstruction throuhg choosing the alike value before sth point.

III. THE PROPOSED METHOD

The vibration signal of early fault of the gearbox contains severe noise, and the weak fault feature information is often overwhelmed and difficult to collect. The proposed ELMD-SVD diagnostic method can extract the weak feature information that characterizes the gearbox fault from the early fault vibration signal effectively. The proposed diagnostic flow chart is plotted in Fig. 1. The details steps of implementation are as shown below:

Step 1: Acquisition the fault vibration signal of gear box.

Step2: The amplitude and integration times of adding white noise in ELMD are determined, and disintegrate the original gearbox fault vibration signal into many narrow-band product functions by ELMD.

Step3: Hankel matrix is refactored at phase space for PF components containing fault features, and the matrix is decomposed by SVD, and then the singular values difference spectrum is used to determine the signal reconstructed order.

Step 4: Envelope demodulation algorithm based on Hilbert transform is performed on the reconfigured signal, and the fault feature information is extracted in the envelope spectrum. Determine the location and type of the gearbox fault by comparing with the expected value.

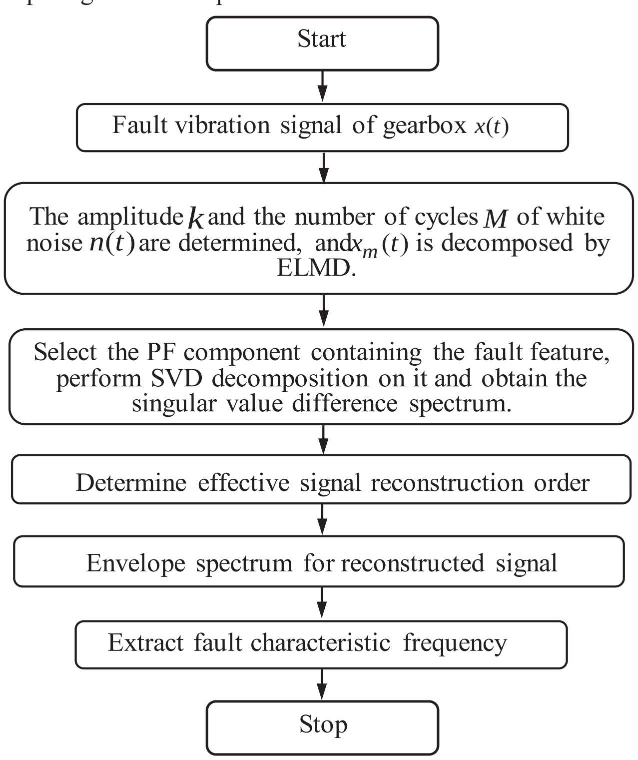


Figure. 1 The flow chart of gearbox fault diagnosis method.

IV. EXPERIMENTAL VERIFICATION

A. Experimental equipment

The Power Drive Fault Diagnosis Comprehensive Test Bed designed by Spectra Quest Company was used to collect the gearbox vibration data and the feasibility and validity of the algorithm are verified. The main component of the test bench is a variable speed drive motor, a two-level planetary gearbox (transmission ratio 4.572:1), a two-level parallel axle gearbox and a programmable magnet brake. Variable speed driving motor connects the sun gear of the primary planetary gearbox, and the secondary planetary gearbox planet frame connects the input axis of gearbox as the input power, thus driving the whole system to work. The experimental platform is presented in Fig. 2. DT9837 data acquisition instrument was chosen as experimental data acquisition device. The parallel shaft gearbox consists of two pairs of gears, the teeth number is Z1 = 100, Z2 = 29, Z3 = 90, Z4 = 36, respectively. The internal structure of parallel shaft gearbox is present at Fig. 3(a). The gear failure part is shown in Fig. 3(b). The sampling frequency is $f_s = 5120$ Hz, and the speed of the motor is 3600r/min (the corresponding rotation frequency is 60Hz). On the basis of the above parameters, the fault frequency feature of the pinion on the intermediate shaft is calculated to be 45.25 Hz.

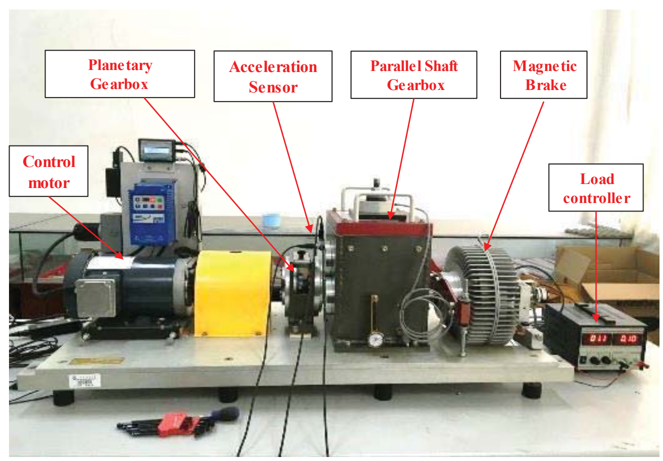
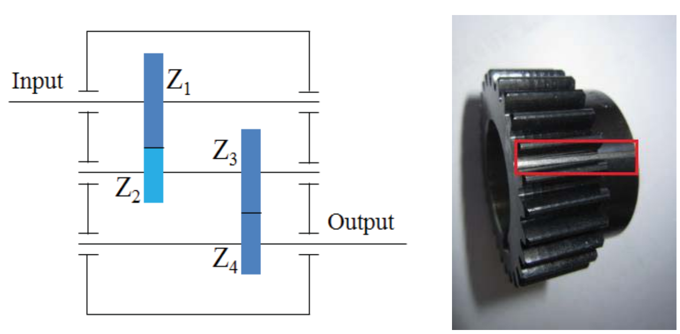


Figure 2. Gearbox fault test bench.



(a) (b)

Figure 3. Internal structure of parallel shaft gearbox and gear fault part in experiment: (a) Structural sketch of parallel shaft gearbox; (b) Gear with root crack fault

B. Analysis and results

The time domain waveform and frequency spectrum of gear crack fault vibration signal are shown in Fig. 4. As display in Fig. 4 (a) that here are many noises in the time domain signal, although some shocks occur sporadically, it is difficult to find the interval between them, which indicates that the strong noise submerges some fault shocks with less energy. Fig. 4 (b) shows that the main frequency component are the meshing frequency of gear and its harmonic, but the spacing of side bands can not be found on both sides of the meshing frequency. Therefore, it is impossible to diagnose the gearbox state only through time domain and traditional Fourier spectrum analysis.

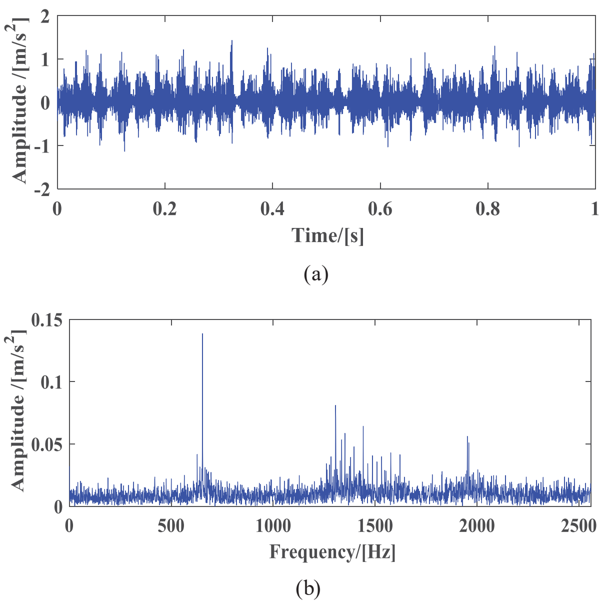


Figure. 4 Fault vibration signal and its spectrum: (a) Time domain waveform; (b) Frequency domain waveform

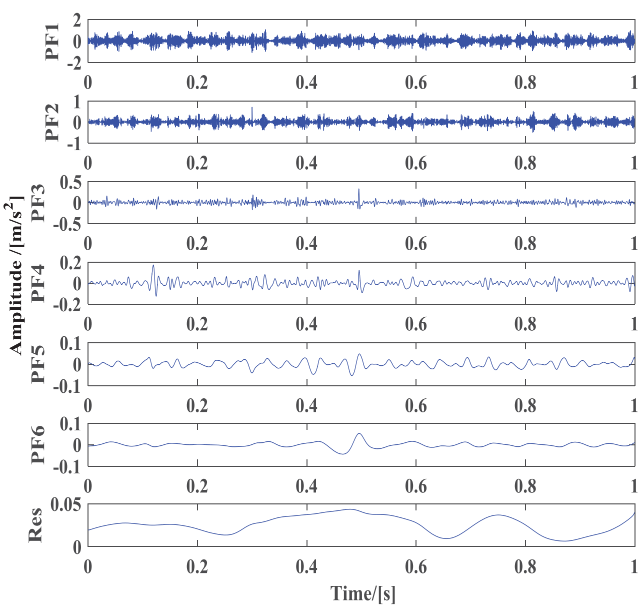


Figure. 5 ELMD decomposition results

In order to extract weak feature information that can characterize the faults of gear, using ELMD to decompose the original vibration signal. Simultaneously, the amplitude of Gaussian noise added to ELMD is 0.02 times of the primary signal variance, and the integrations figure is set up 100 times. The decomposition results are plotted in Fig. 5. Compared with each component, we can find that there is a weak periodic impact component in the PF1 component, so the PF1 component is chosen as the sensitive component to be analyzed.

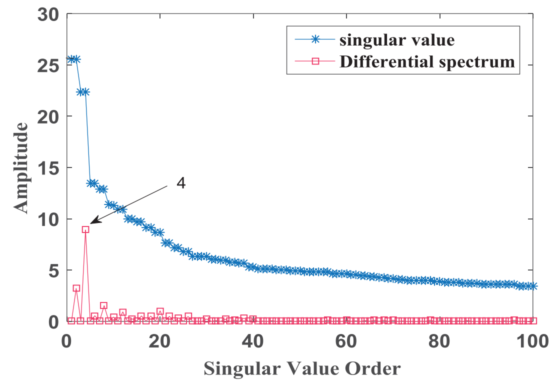


Figure. 6 The first 100 data points of singular value and difference spectrum .

Since that data length of PF1 component is even, according to the construction principle of matrix mentioned in section 2.2, the Hankel matrix is constructed with the number of row m=2561 and the number of column n=2560. The matrix is decomposed orthogonally by SVD, and then the singular value difference spectrum can obtain. From Fig. 6. it shows that the maximum variation coordinate position in the difference spectrum occurs at the fourth point, therefore the first four singular values and their corresponding orthogonal vectors are selected for SVD reconstruction, and the reconstructed signal as display in Fig. 7(a). The waveform in time-domain of the reconstructed signal clearly shows the equal-interval impact with an interval of about 0.022s, its reciprocal approximately corresponds to the intermediate shaft gear frequency, i.e.45Hz.

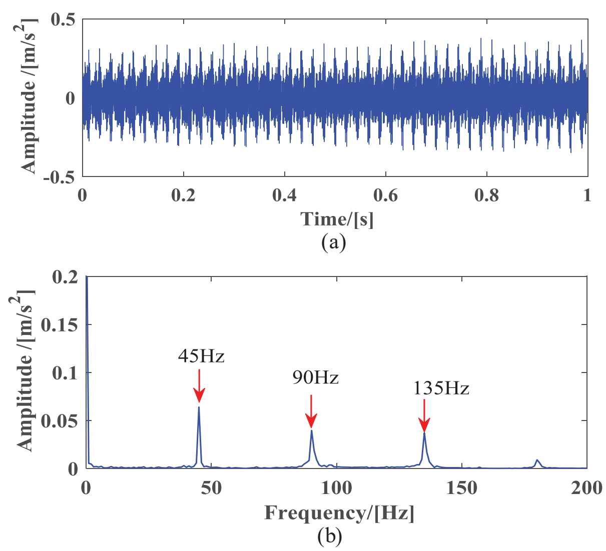


Figure. 7 The processing result of gearbox fault signal by the proposed method: (a) The reconstructed result of the first four singular values, (b) The Hilbert envelope spectrum of reconstructed signal;

As the Fig. 7(b) shown, the envelope spectrum of reconfiguration signal appears obvious peaks at 45Hz, 90Hz and 135Hz, which are exactly corresponding to the characteristic frequency of gear fault of intermediate spindle gear and its harmonic, respectively. The analysis results are consistent with the experimentally set fault. Up to now, the method proposed has realized the accurate diagnosis of gear fault successfully.

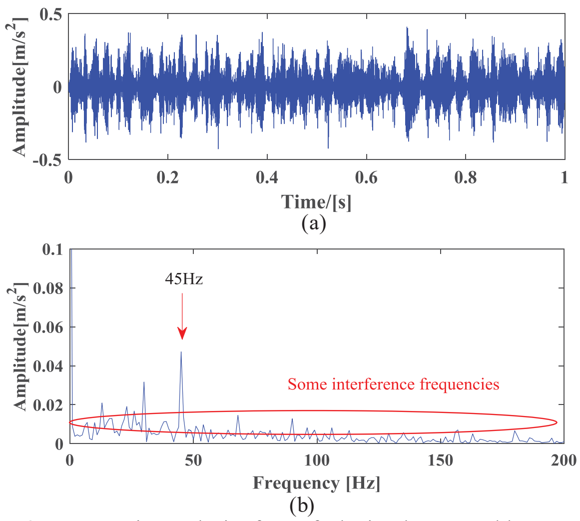


Figure. 8 Comparative analysis of gear fault signal processed by EMD-SVD method: (a) The signal reconstructed result; (b) The Hilbert envelope spectrum of reconstructed signal;

For verify the superiority of the method proposed in this paper, the conventional EMD-SVD method is used to extract the characteristic frequency information in the raw gearbox fault signal, that result is shown in Fig. 8. It shows in Fig. 8(a) that only a few impulse component parts arise in the reconfiguration signal, and the noise reduction effect is not obvious, and it is hard to accurately extract the continuous periodic impact component contained in the gearbox fault signal. In Fig. 8(b), the fault feature frequency of gear appears at the envelope spectrum of the reconstructed signal, but its harmonic frequency components did not appear, and there are many other irrelevant interference frequencies in the spectrum, which cannot correctly reflect the gearbox fault. By comparison, it is found that the method proposed has obvious advantage in extracting early weak impact features of the gearbox.

V. CONCLUSION

This paper put forward a novel and an elegant method ELMD-SVD for gearbox early weak fault diagnosis. The significant conclusions were obtained by analyzing the actual gearbox fault data as follow: (1) The ensemble local mean decomposition method suppresses mode aliasing in local mean decomposition, and its decomposition results can more accurately reflect the characteristics of fault signal. (2) The PF component containing abundant fault feature information is orthogonally decomposed by SVD, and then it can obtain the singular value difference spectrum. The reconstructed signal order can be accurately and automatically selected in the singular value difference spectrum, which avoids the blindness of artificially selecting the reconstructed order and improves the accuracy of fault diagnosis. (3) The actual gearbox fault data analysis demonstrates that the proposed method can extract fault feature information accurately and effectively under high level noise environment, and realize the diagnosis and early warning of gearbox weak faults, which has a certain application value in engineering application field.

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