EMD and Singular Value Difference Spectrum Based Bearing Fault Characteristics Extraction

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Abstract. Aiming at extracting rolling bearing defect characteristic effectively under strong background noise, a defect diagnosis technique based on empirical mode decomposition (EMD) and singular value difference spectrum is put forward. Firstly, the non-stationary original bearing vibration experimental data is decomposed into several intrinsic mode functions (IMFs) using EMD technique to eliminate the noise influence. Secondly, the effective intrinsic mode functions are selected by using correlation functions to reconstruct the bearing transient vibration signal. Thirdly, the singular value decomposition of the reconstructed signal is carried out to calculate the singular value difference spectrum (SVDS), and the principal components are selected according to the SVDS. Finally, the envelope spectrum of the reconstructed principal components data is calculated, and rolling bearing defect characteristic is picked up according to the envelope spectrum technique. The results of the experiment exhibit that the proposed technique can be effectively applied to rolling bearing defect characteristics extraction.

Keywords: Empirical mode decomposition; Fault diagnosis; Bearing; Singular value decomposition; Difference spectrum; Signal procession.

1. Introduction
Rolling bearing is the most extensive applied and easily breakdown mechanical components in rotating machine. Many mechanical defects are related to rolling bearing, so the working condition of bearing has a great influence on the working condition of machinery. Its defects cause abnormal vibration and noise of equipment, even damage to equipment. How to pick up the defect characteristic information from the vibration signal with non-stationary and strong background noise is the key of rolling bearing defect detection. Therefore, last several years, many scholars were devoted to the research of rolling bearing defect detection and recognition. Many techniques based on vibration data analysis have been put forward. These approaches consist of fast Fourier transform (FFT), power spectrum estimation, envelope spectrum analysis and cepstrum analysis technique, and have achieved good results in bearing defect detection and recognition [1]. However, these approaches are the whole based on the hypothesis of stationarity and linearity of experimental data. But the experimental data of rolling bearing defect has the characteristics of non-linear and non-stationary, and the experimental vibration data of rolling bearing defect has the characteristics of transient shock in essence. Therefore, the bearing system fault detection and diagnosis need to study new vibration analysis technology.

A rolling bearing fault monitoring and recognition approach using EMD technique and singular value difference spectrum is proposed. EMD is a modern non-stationary and nonlinear adaptive signal processing technique proposed by Huang [2]. This method has many advantages. EMD can adaptively break up multi-component signals into a great number of zero mean intrinsic mode functions (IMF).
Then, the correlation coefficient is used to select the best intrinsic mode function and reconstruct the bearing fault vibration signal, which effectively suppresses the noise in the experimental data and highlights the transient shock characteristics of the vibration data. Then singular value decomposition is used to the reconstructed signal, and singular value difference spectrum is calculated to correctly select the effective principal components data. Finally, the envelope spectrum of the selected principal components is analyzed, and the bearing fault feature is identified and diagnosed according to the envelope spectrum characteristics of the reconstructed principal components signal. The technique based on EMD and singular value difference spectrum can correctly extract the characteristic frequency of rolling bearing defects. The basic principle of this technique is presented briefly, and it is used to rolling bearing defect detection and recognition. Experimental results demonstrate that this approach can correctly monitor and identify rolling bearing faults.

2. Brief Introduction of EMD

2.1. Definition of IMF

Huang et al [2] defined the intrinsic mode functions as a kind of zero mean values function that the following two basic conditions are satisfied:

i) In the entire dataset, the number of all extremum and zero crossing must be identical or one difference at most;

ii) In the entire sampling interval, at any time, the average value of the envelope expressed using the local maximum and the envelope expressed using the local minimum have to be zero.

2.2. Empirical Mode Decomposition

EMD method is put forward based on the hypothesis of simple morphological diversity, that is, any vibration signal is composed of function superposition with various ordinary intrinsic vibration modes. The nature of this approach is to use the characteristic time scale of the experimental vibration data to identify the intrinsic vibration mode of the signal, and then the signal is adaptively broken up into the sum of several intrinsic mode functions (IMFs). The feature time scale can be given according to the time difference between two consecutive extremes. In order to pick up IMF adaptively from the given experimental vibration signal, the vibration data sifting process is utilized.

The data shifting process of picking up more natural modes $IMF_{cl}(t)$ will be repeated many times to find all the intrinsic mode functions in the signal until the last one is found. The final residue will be a monotonic function or a constant. In general, The error may be the general tendency of the vibration signal.

\[ x(t) = \sum_{i=1}^{n} IMF_{ci}(t) + r_n(t) \]  

After the above steps, the experimental vibration data is finally decomposed into several natural modal functions and error, $r_n(t)$, which can be either a constant or the mean tendency.

The cross correlation function of each IMF and the original vibration signal are calculated to highlight the frequency change characteristics. The cross correlation function is formulated as

\[ R_{iIMF_{cl}}(j) = \frac{1}{N} \sum_{i=0}^{N-1} x(i)IMF_{ci}(i + j) \]  

Then the cross correlation coefficient can be calculated by

\[ \rho(j) = \frac{\sum_{i=0}^{N-1} x(i)IMF_{ci}(i + j)}{\sqrt{\sum_{i=0}^{N-1} x^2(i)\sum_{i=0}^{N-1} IMF_{ci}^2(i)}} \]
3. Singular Value Difference Spectrum

3.1. Singular Value Decomposition (SVD)
Consider a vibration signal given by \( z(n) \), where \( n = 1,2,3,\cdots,N \), \( N \) is the length of \( z(n) \). The Hankel matrix of \( z(n) \) is defined by

\[
HM = \begin{bmatrix}
z(1) & z(2) & z(3) & \cdots & z(N-M+1) \\
z(2) & z(3) & z(4) & \cdots & z(N-M+2) \\
z(3) & z(4) & z(5) & \cdots & z(N-M+3) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
z(M) & z(M+1) & z(M+2) & \cdots & z(N)
\end{bmatrix}
\]

(4)

Where \( M \) is the number of row of Hankel matrix \( HM \in \mathbb{R}^{M \times (N-M+1)} \).
The singular value decomposition of matrix \( HM \) is formulated below

\[
HM = U \Sigma V^T
\]

(5)

Where \( U \in \mathbb{R}^{M \times M} \) and \( V \in \mathbb{R}^{(N-M+1) \times (N-M+1)} \), which are from the SVD, are orthogonal matrix. \( \Sigma \) is a diagonal matrix, whose diagonal elements are \( \sigma_1, \sigma_2, \sigma_3, \cdots, \sigma_r \). \( \sigma_1, \sigma_2, \sigma_3, \cdots, \sigma_r \) are the singular values of Hankel matrix \( HM \).

\[
\Sigma = \text{diag}(\sigma_1, \sigma_2, \sigma_3, \cdots, \sigma_r)
\]

(6)

Where \( r \) is the rank of diagonal matrix \( \Sigma \).
Therefore, the SVD of Hankel matrix \( HM \) can be formulated as follow

\[
HM = \sum_{j=1}^{r} \sigma_j u_j v_j^T
\]

(7)

Where \( v_j \) is the right singular vector and \( u_j \) is the left singular vector, respectively.

3.2. Singular Value Difference Spectrum
After SVD of Hankel matrix \( HM \) is finished, singular value difference spectrum can be computed as follow

\[
S_j = \sigma_j - \sigma_{j+1} \quad j = 1,2,3,\cdots,r
\]

(8)

All \( S_j \) sequences are called the singular value difference spectrum. According to the expression and formula of singular value difference spectrum, the wave spikes in the singular value difference spectrum result from the uncorrelated of noise and valuable signal. In the event of the maximum sudden change happens at the \( j \) point, the noise can be reduced by selecting the order before the \( j \) point to reconstruct the principal components.

4. Bearing Damage Detection Based on EMD and SVDS
The experimental ball bearing is only utilized to research one kind of localized surface defect: bearing inner ring or outer ring defect. The tested rolling bearing is used discharge device to machine a groove on the inner or outer ring. The rolling bearing defect characteristic frequencies of inner ring and outer ring are 148.5Hz and 101.5 Hz [3].
The sampled rolling bearing inner ring defect vibration data is exhibited in Figure 1. The FFT of the vibration data is exhibited in Figure 2. Figure 3 displays the empirical mode decomposition of vibration data with inner ring defect, which has twelve intrinsic mode functions. The cross correlation coefficient of each IMF and the raw vibration data is computed and displayed in Figure 4. The cross correlation coefficient of the first five IMFs has a large value. Therefore, the first five intrinsic mode functions are added to reconstruct the bearing fault vibration signal, which shows in Figure 5.
According to the correlation coefficient of each IMF, the Hankel matrix can be constructed by reconstructed signal. Then the singular value decomposition can be finished, and singular value difference spectrum can be calculated, as given in Figure 6. From Figure 6, one can be sees that the amplitude of the first 21 difference spectrum is large. Therefore, the first 21 principal components signal are reconstructed and then the envelope spectrum of the reconstructed principal component signals can be calculated, as displayed in Figure 7. From Figure 7, the transient impact feature caused by the interaction of roller defects can be clearly seen. In addition, these transient impacts reveal the failure mode of the bearing, corresponding to the bearing inner ring characteristic defect frequency of 148.5Hz, which is caused by the structural defects of the inner ring.
5. Summary

For the sake of effectively extraction the transient impact features of noisy vibration data, a rolling bearing defect detection and recognition approach based on EMD and SVDS technique is carried out, and the validity and reliability of the approach are testified by experimental vibration data. EMD approach is one type of adaptive data decomposition technique, which has the ability of adaptively breaking up the data into the sum of several intrinsic mode functions, and it is very suitable for analyzing non-stationary non-linear and data. Through singular value decomposition and singular value difference spectrum technique, not only the useful information components in the original signal are effectively retained, but also the noise interference is eliminated to the maximum extent. The combination of EMD method and singular value difference spectrum theory is applied to the field of bearing fault diagnosis, which can achieve satisfactory results and provide an effective technique for bearing fault detection and recognition.

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