Rolling Bearing Fault Diagnosis Based on EMD-TEO and Mahalanobis Distance

Lu Chen[1], Hu Jiameng[2], Liu Hongmei[3] and Wang Jing[4]
[1, 2] School of Reliability and Systems Engineering, Beihang University, Beijing, 100191, China
[1, 2, 3, 4] Science & Technology on Reliability & Environmental Engineering Laboratory, Beijing 100191, China

E-mail: hujiamengbrave@163.com

Abstract. A intelligent rolling bearing fault diagnosis method is proposed on Empirical Mode Decomposition (EMD) – Teager Energy Operator (TEO) and Mahalanobis distance. EMD can adaptively decompose vibration signal into a series of Intrinsic Mode Functions (IMFs), that is, zero mean mono-component AM-FM signal. TEO can estimate the total mechanical energy required to generate signals, so it has good time resolution and self-adaptive ability to the transient of the signal, which shows the advantage to detect the signal impact characteristics. With regards to the impulse feature of the bearing fault vibration signals, TEO can be used to detect cyclical impulse characteristic caused by bearing failure, gain the instantaneous amplitude spectrum of each IMF component, then identify the characteristic frequency of the interesting and single IMF component in bearing faults by means of Teager energy spectrum. The amplitude of the Teager energy spectrum in inner race fault frequency, outer fault frequency and the ratio of the energy of the resonance frequency to the total energy were extracted as the feature vectors, which were used as training samples and test samples separately for fault diagnosis. Then the Mahalanobis distances between the real measure and different type overalls of fault sample are calculated to classify the real condition of rolling bearing. Experimental results was concluded that this method can accurately identify and diagnose different fault types of rolling bearing.

1. Introduction

Bearings are an important element in a variety of industrial applications such as machine tool and gearbox. An unexpected failure of the bearing may cause significant economic losses. For that reason, faults detection of bearing has been the subject of intensive research [1].

Signals generated by the rolling bearing failure often contain a large number of non-stationary components. The global frequency domain information can be obtained by fourier transform for signals containing non-stationary composition, and the fault information is difficult to be extracted effectively from spectrum overwhelmed by noise. Local information of non-stationary signals can be extracted by wavelet transform. But the information of high frequency is lost which is caused by lack of the decomposition high-frequency part, so that the fault characteristics of high frequency is difficult to be extracted. Wavelet packet transform makes up for the lack of wavelet transform for high-frequency decomposition. It can have a whole multi-level decomposition in the full-band signal, coupled with good time-frequency characteristics. However, in terms of feature extraction of low signal to noise ratio of the vibration signal, it has no breakthrough.

In this paper, we present a intelligent diagnosis method based on Empirical Mode Decomposition (EMD) Teager Energy Operator (TEO) and Mahalanobis distance. EMD is a fundamentally new approach to the decomposition of nonlinear and nonstationary signal presented originally by Huang [2]. EMD can decompose adaptively signal into a finite and usually small number of Intrinsic Mode Functions (IMFs) which are usually monocomponent Amplitude Modulation-Frequency Modulation (AM-FM) signals. Signal components with amplitude modulation characteristics exist in high frequencies, therefore, IMFs including high frequency are selected for further analysis. In this paper, the appropriate and interested IMF1 is selected to gain feature vectors for the input of TEO because

[2] To whom any correspondence should be addressed.

IMF1 obtain more information of signal characteristics.

TEO is a nonlinear operator, which can track the energy of the interesting Intrinsic Mode Functions (IMFs), gain the instantaneous amplitude spectrum of each IMF component and identify the characteristic frequency of bearing faults by means of Teager energy spectrum [3].

Moreover, the feature frequencies of the inner race and outer race faults, the ratio of the resonance frequency band energy to the total energy in the Teager energy spectrum were extracted as feature vectors, which were used as training samples and test samples separately for fault diagnosis. TEO also enable the extraction of bearing fault feature frequencies for fault detection. In end, the extracted features are classified using the Mahalanobis distances for fault diagnosis of rolling bearing. The result shows that the proposed method is effective.

2. Methodology

2.1. EMD Algorithm

Norden E. Huang and his colleagues developed a method of empirical mode decomposition (EMD) in 1998 [4]. This method decomposes signals into IMFs. The IMF must satisfy two requirements as below: In a series of data, the number of extreme value points and the zero-crossing point must be equal or differ by one point at most. In any point of time axis, the average value of the upper and lower envelope is zero.

The basic algorithm of EMD is as follows, therein $x(t)$ is the original signal sequence

(1) Initialize $h \leftarrow x(t)$.

(2) Search all the maximum and minimum values of *h*.

(3) The upper and lower envelope is fitted by cubic-spline, and the mean value *m* of the upper and lower envelope is calculated.

(4) The mean value of envelope is subtracted from the sequence *h*, $h \leftarrow h - m$.

(5) Repeat step 2) ~ step 4) ,until h is an IMF.

(6) $I \leftarrow I - h$, repeat the steps from (1) to (5) until the last sequence *m* cannot be decomposed anymore.

The result of EMD can be written as below:

$$x(t)=\sum_{i=1}^{n} IMF_i + r_n \tag{1}$$

2.2. Teager Energy Operator (TEO)

The TEO, $\psi(.)$ is defined for continuous-time signal $x(t)$ as[5]:

$$\psi\left[x(t)\right]=\left[\dot{x}(t)\right]^2 - x(t)\ddot{x}(t), \tag{2}$$

where $\dot{x}(t)$ and $\ddot{x}(t)$ represent the first and second time derivatives of $x(t)$ respectively. In fact, the output of the Teager Energy Operator tracks the total energy required to produce a signal.

$$x(t) = A\cos(\omega t + \psi) \tag{3}$$

where A represents the amplitude of the vibration, ψ represents the initial phase.

At any time the mechanical energy of the vibration system is the sum of the potential energy of the spring and the kinetic energy of the mass:

$$E = \frac{1}{2}k\left[x(t)\right]^2 + \frac{1}{2}m\left[\dot{x}(t)\right]^2 \tag{4}$$

The total energy can be written as

$$E = \frac{1}{2} m A^2 \omega^2 \quad (5)$$

Equation (5) shows the instantaneous total energy of the harmonic vibration and the square of the amplitude is inversely proportional to the square of the frequency. From the above equations, we can get:

$$\psi\left[x(t)\right] = \psi\left[A\cos(\omega t + \psi)\right] = A^2\omega^2 \quad (6)$$

Contrasting to (5) and (6), there is only a difference of a constant m/2 between the output of the TEO and the instantaneous total energy of simple harmonic motion.

In the discrete case, the time derivatives may be approximated by time differences.

The discrete-time counterpart of TEO becomes [6]:

$$\psi\left[x(n)\right] = \left[x(n)\right]^2 - x(n-1)x(n+1) \quad (7)$$

For the discrete-time signal, TEO only need 3 samples to calculate the energy of the signal at any time. Therefore, TEO has a good time resolution for the instantaneous change of the signal, and can detect the transient components of the signal.

2.3. Diagnosis approach for rolling bearing

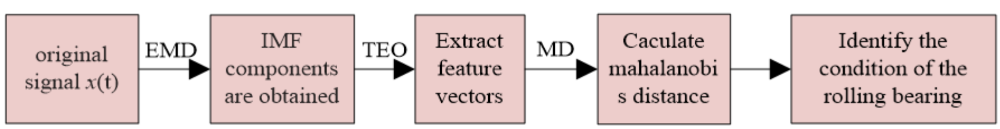

Figure 1. Flow chart of the proposed method.

The fault diagnosis method for the rolling bearing is as shown in Figure1:

(1) Each signal is decomposed by EMD, and a finite number of IMF components can be obtained. Select the appropriate and interesting Intrinsic Mode Functions (IMFs) for the input of TEO.

(2) TEO gain the instantaneous amplitude spectrum of each IMF component and identify the characteristic frequency of bearing faults by means of Teager energy spectrum for fault detection. Moreover, the feature frequencies of the inner race and outer race faults, the ratio of the resonance frequency band energy to the total energy in the Teager energy spectrum were extracted as feature vectors, which were used as training samples and test samples separately.

(3) The Mahalanobis distances between the test sample and different type overalls of fault samples are calculated to classify the real condition of a rolling bearing.

(4) Identify the condition of the rolling bearing.

3. Case study

3.1. Experiment setup

This paper uses the data from bearing data center of Case Western Reserve University for testing and verification. As shown in Figure 2, test rig consists of a 2hp (horsepower) motor (left), a torque converter / encoder (in), a dynamometer (right) and the control circuit (not shown). A deep groove ball bearing of 6205-2RS JEM SKF is mounted in the motor. An acceleration sensor installed on the magnetic base shell is used to collect vibration datas. Vibration signals collected by sensors include normal signal, inner race fault signal, outer race fault signal, and the sampling frequency is 12khz. The experimental datas were collected from 30 groups of samples. It was composed of three types of conditions (normal, inner race fault, outer race fault), each of which includes 10 groups of samples. Here, the first six groups were selected as training samples, and the remaining four groups as testing samples.

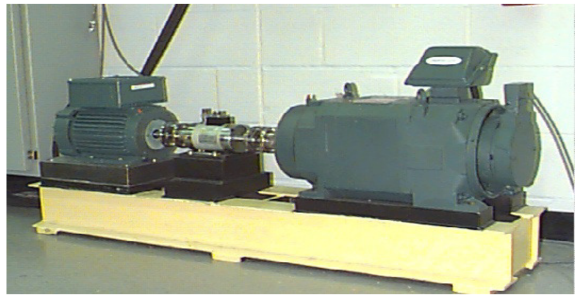

Figure 3. Experimental setup.

3.2. Feature extraction based on EMD-TEO

Figure 3 and Figure 4 show the IMFs obtained by EMD. The original signal can be decomposed into 4 IMFs and one residue. The amplitudes of IMF3 and IMF4 are more little comparing with others. So IMF3 and IMF4 can be abandoned. To select the interested IMF1 component for the input of TEO according to the objective of fault diagnosis because IMF1 contains the highest signal frequencies. The transient caused by the bearing faults is clearly captured. From Figures 3 and 4, it can be easily proven that the EMD decomposes vibration signal very effectively on an adaptive method.

The amplitude of the Teager energy spectrum in inner race fault frequency, outer fault frequency and the ratio of the energy of the resonance frequency to the total energy are extracted as the feature vectors. For avoiding the error of the frequency leak, the weighted of Teager spectrum in fault frequency and $\Delta f = 2$Hz around were extracted as the feature vectors.

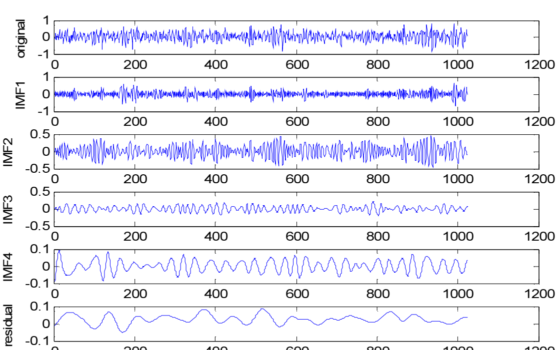

Figure 3. IMFs of the inner race vibration signal.

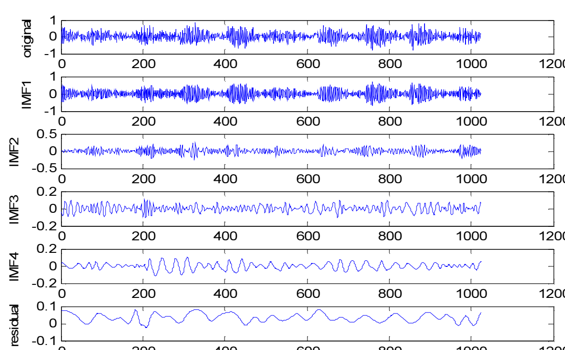

Figure 4. IMFs of the outer race vibration signal.

3.3. Pattern Recognition

3.3.1. Fault detection based on the TEO. Cyclical shock will generate when the fault bearing works. The frequency of this cyclical shock reflects the reason of the bearing fault. According to the parameters of the rolling bearings, fault characteristic frequencies of each element were calculated respectively. The results are as follows: f_{inner}=157.94Hz, f_{outer}=104.56Hz.

The TEO can be applied to each IMF component, resulting in Instantaneous amplitude signal. Figure 5 and Figure 6 respectively are instantaneous amplitude of IMF1 component for the inner race and outer race fault bearing. After the EMD, in addition to the effects of low frequency noise, when bearing fault impact other parts, the peak of high-frequency vibration sequence is obvious. The above results show that the instantaneous amplitude spectrum of IMF1 is to the best effect.

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Therefore, the IMF1 is selected to identify the characteristic frequency of bearing faults through the Teager energy spectrum. In Figure 7, TEO highlights the cyclical impact characteristics, the fault characteristic frequency(157Hz, close to f_{inner}) and the frequency doubling of the rolling bearing with inner race fault can be clearly identified. Therefore, the IMF1 is related to the inner race defect of the bearing and can be selected as a suitable diagnostic feature in the analysis of the inner race defect. In Figure 8, the fault characteristic frequency (107Hz, close to f_{outer}) and the frequency doubling of the ball bearing with outer race fault can be clearly identified. Therefore, the IMF1 is related to the inner race defect of the bearing and can be selected as a suitable diagnostic feature in the analysis of the outer race defect.

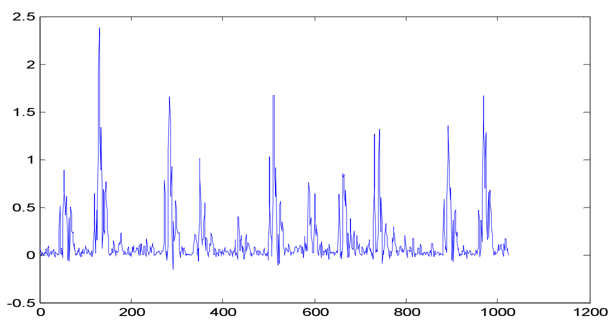

Figure 5. Instantaneous amplitude of IMF1 in the inner race fault condition.

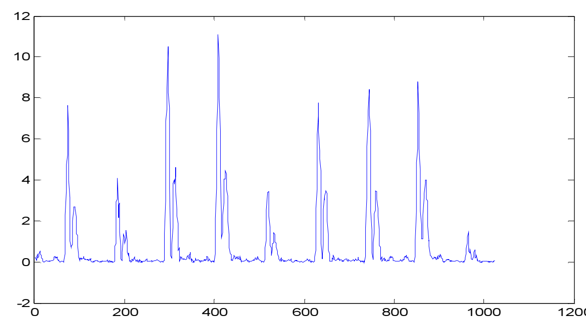

Figure 6. Instantaneous amplitude of IMF1 for the outer race fault condition.

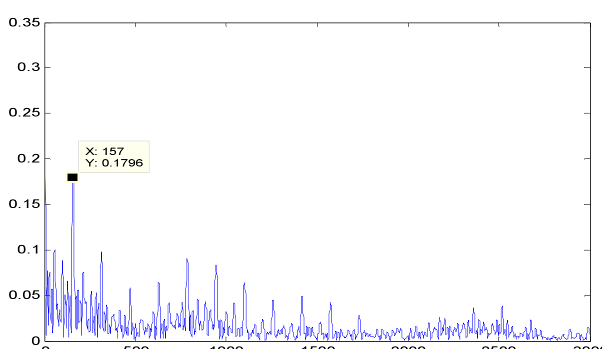

Figure 7. Teager energy spectrum of the inner race fault condition.

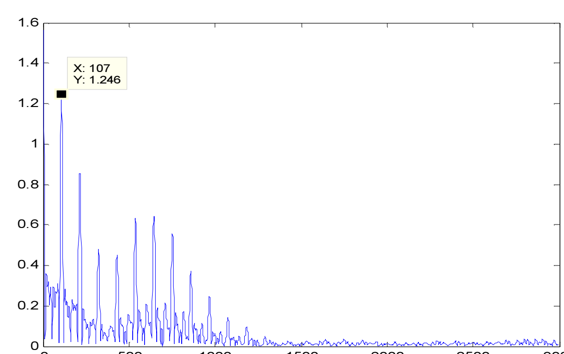

Figure 8. Teager energy spectrum of the outer race fault condition.

3.3.2. Intelligent fault diagnosis based on Mahalanobis distance. Calculate and compare the mahalanobis distance $d^2\left(X,G_i\right)$ $\left(i=1,2,3,\ G_1\text{:normal; } G_2\text{: inner race fault; } G_3\text{: outer race fault}\right)$ from the unknown test sample X to the three overall G_i, then identify the test sample X belong to the G_i of the smallest distance. The criterion is that if $d^2\left(X,G_i\right)=\min d^2\left(X,G_j\right)$, the sample is determined from the overall G_i [7]. Finally, it is distinguished its category of the fault according to the "proximity" principle. The results are shown in Table 1.

Table 1. The results of fault diagnosis

	N_1	N_{22}	N_3	N_4	I_1	I_2	I_3	I_4	O_1	O_2	O_3	O_4
G_1	0.0132	0.0254	0.0175	0.0569	1.2433	1.2719	1.1806	1.2031	1.3593	1.4025	1.3061	1.3446
G_2	1.3475	1.3988	1.3120	1.3624	0.0543	0.0481	0.0395	0.0456	0.0897	0.0847	0.0796	0.0872
G_3	1.4302	1.5895	1.5037	1.5496	0.1654	0.1876	0.1004	0.1263	0.0174	0.0152	0.0160	0.0229
Min	0.0132	0.0254	0.0175	0.0569	0.0543	0.0481	0.0395	0.0456	0.0174	0.0152	0.0160	0.0229
Mod	F_N	F_N	F_N	F_N	F_I	F_I	F_I	F_I	F_O	F_O	F_O	F_O

N_i $(i = 1, 2, 3, 4)$: Mahalanobis distance of the four testing samples under normal condition

I_i $(i = 1, 2, 3, 4)$: Mahalanobis distance of the four testing samples under inner race fault

O_i $(i = 1, 2, 3, 4)$: Mahalanobis distance of the four testing samples under outer race fault

F_N: normal F_I: inner race fault F_O: outer race fault

4. Conclusions

In this paper, a method for fault diagnosis of rolling bearing is presented based on a newly developed signal processing technique named as EMD-TEO and Mahalanobis distance. The EMD-TEO can extract the transient impact feature of the faulty bearing and fault detection, and the Mahalanobis distance can classify the bearing failure mode. EMD acts as a multi-band filter and can adaptively decompose complex signal into a series of IMFs, that is, zero mean mono-component AM-FM signal. TEO tracks the modulation energy of the interesting Intrinsic Mode Functions (IMFs) for feature vectors. And TEO can be used to detect period impulse characteristic of bearing localized damage, and then identify the characteristic frequency of bearing faults by means of Teager energy spectrum. The experimental results show the robustness and the effectiveness of this proposed method.

Acknowledgements

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References

[1] Li H, Fu Lihui and Zhang Y P 2009 *International Conference on Measuring Technology and Mechatronics Automation*
[2] Huang N E, Shen Z and Long S R 1999 *Annual Review of Fluid Mechanics* **31** 417-457
[3] Wang T J, Feng Z P, Hao R J and Chu F L 2012 *Journal of vibration and shock* **31**
[4] Huang N E, Shen Z and Long S R et al 1998 *Proc. R. Soc. Lond.* A **454** 903–95
[5] Potamianos A and Maragos P. 1994 *Signal Processing* **37** 95–120
[6] Maragos P, Kaiser J F and Qu T F 1993 *IEEE Transactions on Signal Processing* **41** 3024–51
[7] Zhang D X and Wu X P 2009 *Anhui University Journal:Natural Science*