A Bearing Fault Diagnosis Strategy Based on Complete Ensemble Empirical Mode Decomposition with Adaptive Noise and Correlation Coefficient Method

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Abstract: In response to the difficulties in extracting fault features from bearing vibration signals and the serious mode mixing and endpoint effects in traditional empirical mode decomposition (EMD) methods, a bearing fault diagnosis strategy combining complete ensemble empirical mode decomposition with adaptive noise(CEEMDANAN) and correlation coefficient method is proposed. This method fully combines the advantages of CEEMDANAN algorithm and correlation coefficient method in signal random detection. Firstly, CEEMDANAN decomposition is performed on the bearing vibration signals to obtain a series of intrinsic mode function (IMF) components. Select IMF components with high correlation coefficients for Hilbert envelope spectrum analysis to achieve bearing fault diagnosis. The experimental results show that the proposed method can effectively achieve fault diagnosis of bearings.

Keywords: EMD; CEEMDAN; Correlation Coefficient Method; Bearing Fault Diagnosis; Hilbert Envelope Spectrum Analysis

1. Introduction

As a core component in mechanical systems, the health status of bearings directly affects the normal operation of the entire mechanical system [1, 2]. Therefore, it is necessary to accurately diagnose the status and faults of bearings. Due to the strong nonlinearity and non stationarity of bearing vibration signals, time-frequency analysis methods are needed to extract features from bearing vibration signals. Common methods include wavelet transform [3], empirical mode decomposition (EMD) [4], etc. However, the decomposition effect of wavelet transform method is mainly affected by wavelet bases, and the algorithm's decomposition effect is unstable. The decomposition effect of EMD is limited by its mode mixing effect. The CEEMDAN method decomposes complex vibration signals into multiple intrinsic mode components (IMFs) that are related to the sampling frequency and changes in the signal itself, which can effectively reduce the mode mixing effect of EMD methods [5].

To solve the problem of difficulty in feature extraction, this paper combines the CEEMDANAN method with the correlation coefficient method to extract and select features of bearing vibration signals. The obtained IMFs are used for fault diagnosis using envelope analysis method. The chapter arrangement of this article is as follows: The second part introduces the basic principles of the CEEMDANAN method and correlation coefficient method, the third part introduces the basic steps of the proposed method, and the fourth part is the experimental simulation part. The effectiveness of the proposed method is verified using experimental data and the method proposed in this article.

2. Theoretical Background

2.1 CEEMDANAN Method

EMD is a new adaptive time-frequency analysis method developed in recent years, widely used in the analysis and processing of nonlinear signals [6]. This method can adaptively decompose the signal based on its own scale, without the need to preset any basis functions. Its disadvantage is the existence of modal aliasing phenomenon. In response to the above shortcomings, scholars have proposed the Ensemble Empirical Mode Decomposition (EEMD) method, which uses multiple additions of white noise and multiple solutions to obtain IMF components [7]. Then, by calculating the average value, the goal of eliminating the added white noise is achieved. This method can suppress modal aliasing, but the disadvantage is that the addition of white noise affects signal reconstruction. Based on this, scholars have proposed the CEEMDANAN method [8], which adds white noise with opposite positive and negative values to the signals, which can avoid the noise residue problem of the EEMD method and suppress modal aliasing effects. The main process of the CEEMDANAN method is:

Add Gaussian white noise $W^i(n)$ that obeys $N(0,1)$ to the original signal $X(n)$.

$$\hat{X}(n) = \eta_0 W^i(n) + X(n) \tag{1}$$

Where, $\hat{X}(n)$ is the signal after adding noise, and η_0 is the amplitude adjustment coefficient.

Perform a layer of decomposition on $\hat{X}(n)$ to obtain the first modal component $\overline{IMF_1}(n)$ and residual $r_1(n)$, with a decomposition level of $I=1$.

$$\overline{IMF_1}(n) = \frac{1}{I}\sum_{i=1}^{I} IMF_1^i(n) \tag{2}$$

$$r_1(n) = X(n) - \overline{IMF_1(n)} \tag{3}$$

Perform two-layer decomposition on $r_1(n) + \eta_1 EMD_1(W^i(m))$ to obtain $\overline{IMF_2}(n)$ and residual $r_2(n)$, with a decomposition level of $I=2$.

$$\overline{IMF_2}(n) = \frac{1}{I}\sum_{i=1}^{I} EMD_1(r_1(n) + \eta_1 EMD1(W^i(n)) \tag{4}$$

$$r_2(n) = r_1(n) - \overline{IMF_2}(n) \tag{5}$$

Repeat steps 2 - 3 to decompose the signals step by step until the residual signal is a monotonic function. After decomposition, the original signals can be represented as:

$$X(n) = \sum_{K=1}^{K} \overline{IMF_k}(n) + R(n) \tag{6}$$

Where, $\overline{IMF_K}(n)$ is the K-th modal component, and $R(n)$ is the final residual.

Correlation coefficient method

For a series of IMFs obtained using the CEEMDAN method, there are some false components and interference components. This article uses the correlation coefficient method to remove false components [9]. Calculate the correlation coefficient C between the original signal $x(n)$ and $IMF_i(n)$ as follows:

$$C = \frac{\sum_{i=0}^{L} x(n)\hat{IMF}_i(n)}{\sqrt{\sum_{i=0}^{L} \hat{x}^2(n) + \sum_{i=0}^{L} IMF_i^2(n)}} \tag{7}$$

Where, L is the data length, and $i = 1,2\cdots,n$ is the number of IMFs.

3. Fault Diagnosis Process based on CEEMD and Correlation Coefficient Method

The specific steps for bearing fault diagnosis based on the combination of CEEMDANAN and correlation coefficient method are as follows:

(1) The bearing vibration signals are decomposed using the CEEMDANAN method to obtain a series of IMFs.

(2) Calculate the correlation coefficient values between each IMF and the original components, and arrange them accordingly.

(3) Select multiple components of the IMF that rank higher and use them for signal reconstruction.

(4) Use envelope analysis for bearing fault diagnosis.

4. Experimental Analysis

Using the experimental dataset from the Electrical Engineering Laboratory of Case Western Reserve University [10] as the data source for this experiment. The experimental platform, as shown in Figure 1, consists of a 2-motor, a torque sensor, an encoder, a dynamometer, and control electronic devices. The bearing model is 6205-2RSJEM SKF. Vibration data is collected at a speed of 48000 samples per second, and the accelerometer is connected to a casing with a magnetic base. Using discharge machining to manufacture motor bearing faults. The defect locations are the inner ring, outer ring, and ball, with defect diameters of 0.007, 0.014, and 0.021 inches, respectively. Reinstall the faulty bearing into the test motor, with motor speeds of 1730, 1772, 1797, 1750 RPM units respectively.

The bearing parameters are shown in Table 1.

The fault characteristic frequencies of the inner ring, outer ring, and ball of the bearing can be calculated using equations (8), (9), and (10), respectively:

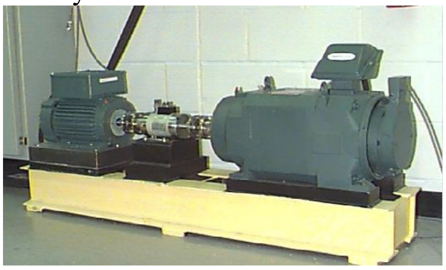

Figure 1. Case Western Reserve University

$$F_{BPFi}=\frac{n}{2}f_r[1+\frac{d}{D}\cos(a)]Hz \quad (8)$$

$$F_{BPFo}=\frac{n}{2}f_r[1-\frac{d}{D}\cos(a)]Hz \quad (9)$$

$$F_{ball}=\frac{D}{d}f_r[1-(\frac{d}{D}\cos(a))^2]Hz \quad (10)$$

Where, D is the middle diameter, n is the number of balls, d is the ball diameter, α is the contact angle (rad), and f_r is the rotational frequency (Hz).

According to the parameters in Table 1 and the above equations, the characteristic frequency of bearing faults can be obtained as shown in Table 2.

Table 1 Bearing Parameters

Content	Parameter
Bearing model	6205-2RSJEM SKF
Inside diameter	25 mm
Outside diameter	52 mm
Thickness	15 mm
Diameter	39 mm
Ball diameter	8 mm
Number of ball bearings	9
Contact angle	0 rad

Table 2 Fault Characteristic Frequencies

Rotational speed	Inner ring fault frequency	Out ring fault frequency	Ball fault frequency
1797	162.44	107.10	139.86
1772	160.18	105.61	137.91
1750	158.20	104.30	136.20
1730	156.36	102.93	134.64

Taking the inner ring fault as an example, the vibration signals with a fault diameter of 0.007 inches is shown in Figure 2a). The CEEMDANAN method is used for decomposition, and the first four IMFs obtained are shown in Figure 2b) - e). Calculate the correlation coefficient values of four IMFs and bearing vibration signals, as shown in Figure 2f). Where, the correlation coefficient values of the first and second IMFs are significantly higher than the other components. Therefore, they are used as feature vectors and the signals are reconstructed. Finally, envelope analysis is used to determine the fault type, and the obtained envelope analysis results are shown in Figure 3.

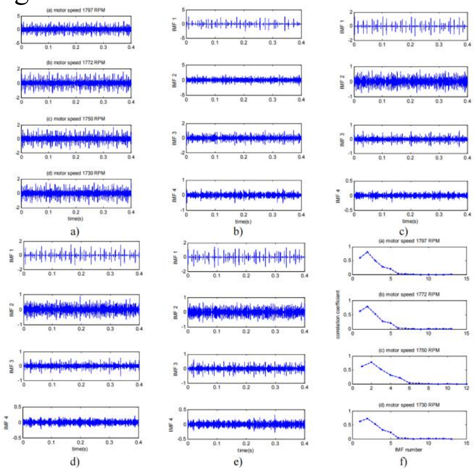

Figure 2. Inner Ring Fault Signal with Defect Size of 0.007 Inches. a) Bearing Vibration Signals b) IMF Signals with a Speed of 1797, c) IMF Signals with a Speed of 1772, d) IMF Signals with a Speed of 1750, e) IMF Signals with a Speed of 1730, f) Correlation Degree Values between the Four IMFs and Bearing Vibration Signals

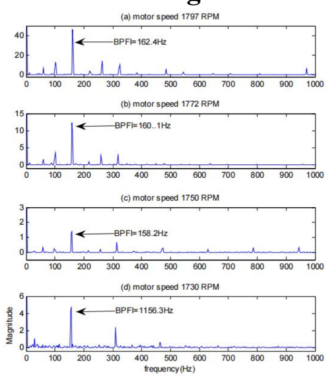

Figure 3. Inner Ring Fault Envelope Analysis Results

According to Figure 3, when the defect diameter is 0.007 inches, the fault characteristic frequencies obtained from the envelope analysis results at different speeds are basically consistent with the results in Table 2. For example, the frequency of the envelope analysis results at 1797 RPM is 162.4 Hz, which is basically consistent with the calculated 162.44 Hz, and the frequency of the envelope analysis results at 1772 RPM is 160.1 Hz, which is basically consistent with the calculated 160.18 Hz, The frequency of the envelope analysis result when the motor speed is 1750RPM is 158.2Hz, which is consistent with the calculated 158.20Hz. The frequency of the envelope analysis result when the motor speed is 1730RPM is 156.3Hz, which is basically consistent with the calculated 156.36Hz. Therefore, it can be determined that the bearing fault type is inner ring fault.

The vibration signals of inner ring defects with diameters of 0.014 inches and 0.021 inches are also processed using the method proposed in this paper. Figures 4 a) and 5 a) show inner ring defect signals with diameters of 0.014 inches and 0.021 inches, respectively. The vibration signals are decomposed into multiple IMF components using the proposed CEEMDAN method, and the IMFs are filtered using correlation coefficients to reconstruct the signals. The results are shown in Figures 4 b) and 5 b). Finally, the reconstructed signals are used for bearing fault diagnosis using envelope analysis. The results of envelope analysis are shown in Figures 4 c) and 5 c).

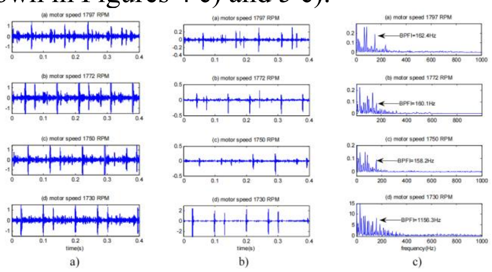

Figure 4. Bearing Signals for Inner Ring Defects with a Diameter of 0.014 Inches: a) Vibration Signals, b) Reconstruction Signals, c) Envelope Analysis Results

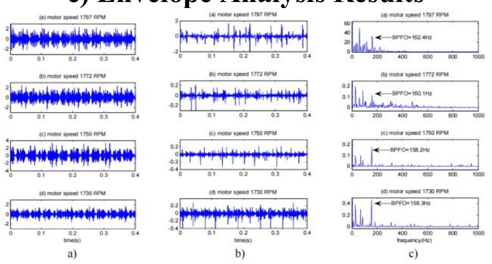

Figure 5. Bearing Signals for Inner Ring Defects with a Diameter of 0.021 Inches: a) Vibration Signals, b) Reconstruction Signals, c) Envelope Analysis Results

According to Figures 4c) and 5c), it can be seen that for the vibration signals of bearings with defect diameters of 0.014 inches and 0.021 inches, the fault characteristic frequencies obtained from envelope analysis at different speeds are basically consistent with the results in Table 2. For example, the frequency of envelope analysis at 1797 RPM is 162.4 Hz, which is basically consistent with the calculated 162.44 Hz. The frequency of envelope analysis at 1772 RPM is 160.1 Hz, which is basically consistent with the calculated 160.18 Hz. The frequency of envelope analysis at 1750 RPM is 158.2 Hz, which is consistent with the calculated 158.20 Hz. The frequency of envelope analysis at 1730 RPM is also consistent with the calculated 158.20 Hz. The 156.3Hz is basically consistent with the calculated 156.36Hz, so it can be determined that the bearing fault type is inner ring fault. Due to space limitations, experiments are conducted using the example of a bearing inner ring fault, and the other two types of faults can be proven similarly.

5. Conclusion

This article proposes a bearing fault diagnosis strategy that combines CEEMDAN with correlation coefficient method. Using the CEEMDAN method to process the bearing vibration signals, a series of IMFs are obtained. The correlation coefficient values between the IMFs and the original bearing vibration signals are calculated using the correlation coefficient method. After removing false components based on the correlation value, the signals are reconstructed. The envelope analysis method is used to demodulate and analyze the reconstructed signals, achieving bearing fault diagnosis. Finally, the reliability of the proposed method is verified through experiments. The experiment analyzed the inner ring fault as an example, and the results showed that the proposed method can effectively achieve accurate diagnosis of bearing faults.

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