Fault diagnosis of rolling bearing based on improved EMD algorithm

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Abstract. The EMD (Empirical mode decomposition) is a good method to diagnose faults of equipment, but the endpoint effect and false IMF (Intrinsic Mode Function) of EMD seriously affects the effect of fault diagnosis. So this paper used an adaptive waveform matching extension algorithm to restrain the endpoint effect. To select effective IMF, moreover, this paper put forward another method which is based on information entropy and kurtosis value. Finally, the paper used the two methods combined with HHT to diagnose the bearing fault, the experimental results show that the above problems have been effectively solved and the fault diagnosis effect has been significantly improved.

1. Introduction

As one of the important parts of rotating machinery, rolling bearing is widely used and plays an important role. According to statistics, up to 30% of rotating mechanical equipment problems are caused by bearing faults every year [1]. Therefore, it is of great significance to extract characteristic information of bearing faults and accurately identify bearing faults to improve equipment reliability, reduce equipment failure rate and reduce the occurrence of equipment problems [1].

Traditional fault diagnosis techniques [2] can be divided into time-domain analysis, frequency-domain analysis and time-frequency analysis. Although short-time Fourier Transform (STFT) can be used for both time-domain and frequency-domain analysis, the time-frequency resolution cannot be optimized at the same Time due to the limitation of window function. Wavelet Transform (WT) improves the time-frequency resolution by changing the size and position parameters of the parent Wavelet, but is limited by the uncertainty principle in time-frequency localization [3]. In addition, the finiteness of the number of small and medium wave bases in Wavelet Transform is also easy to cause energy leakage [4]. According to the above problem, The EMD method [5] as a time-frequency analysis method does not need to rely on basis Function, can be directly to the signal itself information decomposition, the original complex signal is decomposed into a series of smooth, linear, and has the characteristics of different scales of IMF [6]. Compared with STFT and WT, the EMD method is not restricted by the basis function, so it has better adaptability, and EMD method is also very suitable for the analysis of non-stationary and nonlinear vibration signals such as rolling bearing faults [7]. However, after 20 years of development and improvement, EMD technology still has some shortcomings and in the two aspects: endpoint effect and selection of IMF component. Therefore, this paper improves and optimizes EMD technology in the following two aspects.

1. Endpoint effect [8][9]. The endpoint effect refers to that after the signal is decomposed by EMD method, the decomposed signal at the endpoint of the IMF component will show serious distortion,
and will extend from the endpoint to the internal, gradually affecting the whole IMF component signal, thus affecting the accuracy of fault diagnosis.

Because the endpoint effect is caused by the distortion of the endpoint signal caused by the cubic spline interpolation method, in order to suppress the endpoint effect two methods have been proposed according to the causes: the improved interpolation method and the extension method. The extension method has become the main research direction because of its obvious effect and simple method. At present, the common continuation methods include matching continuation, mirror continuation, similar extremal continuation and polynomial fitting continuation. Xu [10] used mathematical simulation experiments to compare the above methods, and the experimental results showed that the adaptive waveform matching continuation method was superior to other continuation methods. Although the self-adaptive matching waveform continuation method has a good effect, the effect of suppressing the endpoint effect is also different for different waveforms. Wang [9] proposed the self-adaptive triangular wave matching extension method by comparing and analyzing the continuation effect of various waveforms, and achieved a good effect in suppressing the endpoint effect. On the basis of the above algorithms, an adaptive waveform matching continuation algorithm is used to suppress the endpoint effect.

2. IMF weight selection. At present, there are few studies on the selection of IMF components. Ding proposed in literature [11] that only a few IMF components in EMD decomposition can reflect fault characteristics, while other IMF components may present noise components at high frequencies or false components with low frequencies. Therefore, how to choose IMF component with obvious fault characteristics also becomes a difficult problem. Therefore, Li [12] proposed shannon entropy method. Zhu used the screening method of kurtosis value. This paper uses the above two methods to screen the effective IMF components.

The steps of this paper are as follows:
(1) EMD algorithm was used to decompose the fault signal of the bearing inner ring, and a group of IMF was obtained.
(2) Using the matching continuation algorithm to suppress the endpoint effect in each IMF component;
(3) Calculating the kurtosis value of each IMF component and the information entropy of response time-frequency distribution, and screen the effective IMF component by combining the two methods;
(4) Hilbert envelope was applied to the screened IMF component, and fault characteristics were extracted for fault diagnosis.

The flow chart is shown in Figure 1.

![Figure 1. The flow chart of fault diagnosis based on improved EMD.](image)

![Figure 2. Diagram of waveform matching extension.](image)
2. Restrain the endpoint effect

At present, there are many methods to suppress the endpoint effect. In this paper, the endpoint effect suppression algorithm based on adaptive waveform matching extension is used to reduce the uncertainty caused by human factors.

2.1. Adaptive waveform matching extension algorithm

The basic introduction of the algorithm is shown in the above Figure 2. By comparing the waveform at the endpoint with the part of the whole waveform, the adaptive waveform matching continuation algorithm selects the part with the closest similarity to the waveform at the end point as the optimal selection of the endpoint continuation.

Firstly, the meaning of matching degree is clarified. Waveform matching degree is an index used to reflect the similarity of two waveforms.

Taking the following situation as an example, the actual meaning and calculation formula of the matching degree are briefly introduced.

Let \( x(t) \) and \( y(t) \) be two sets of data sequences with the same dispersion degree, \( P_1 \) and \( P_2 \) are the above two points respectively. Firstly, shift \( y(t) \) until \( P_1 \) and \( P_2 \) coincide, and then write this as \( y'(t) \). The formula for calculating the matching degree is as follows:

\[
M(x_i, y_i, p_1, p_2) = \sum_{i=0}^{k} [x_i(t_i) - y'_2(t_i)]^2
\]  

(1)

Where \( k \) represents the number of points that \( x_i(t) \) and \( y_i(t) \) coincide with each other.

For continuous signals, the calculation formula is as follows:

\[
M(x_i, y_i, p_1, p_2) = \int_{t_0}^{t} [x_i(t) - y'_2(t)]^2 dt
\]  

(2)

The steps of the adaptive waveform matching method to suppress the endpoint effect can be divided into the following five steps [13]:

1. Assume that the maximum point in the original signal \( x(t) \) is \( m_i \) (\( i = 0, 1, 2, \ldots \)) and the minimum point is \( n_j \) (\( j = 0, 1, 2, \ldots \)), and the two extreme points at the left most end are respectively the maximum point \( m_0 \) and the minimum point \( n_0 \). The waveform segment from the left endpoint to \( n_0 \) is denoted as \( L \).

2. Take the maximum point \( m_i \), which does not include \( m_0 \), as the reference point, and shift \( w_0 \), until \( m_0 \) and \( m_i \) correspond. The \( w_0 \) after the shift is denoted as \( w_0' \). The part corresponding to \( w_0' \) and of equal length is denoted as \( w_i \) from the waveform where \( m_i \) is located.

3. When \( i = k \), write the minimum \( M_k \) as \( M_k \).

4. When \( M_k < a \times L \) (\( a \) is a constant), then considering \( w_k \) is the most similar as \( w_0 \). Therefore, the left-most wavelet of band \( w_k \), including a maximum and a minimum, is taken as the left-most continuation of the original signal \( x(t) \).

5. When \( M_k \geq a \times L \), the mean value of the two maximum points \( m_0 \) and \( m_i \) to the left of the original signal \( x(t) \) is taken as the maximum value of the left continuation, and the mean value of the
two minimum points $n_{0}$ and $n_{1}$ to the left is taken as the minimum value of the left continuation, then the left continuation is finished.

(5) The extension of right side is the same as the above method.

3. To select IMF based on information entropy and kurtosis.

3.1. Information entropy

Information entropy is a physical quantity used to measure the degree of system chaos in physics. Generally speaking, the higher the entropy, the more chaotic the system is; The smaller the entropy, the more ordered the system.

Suppose a sequence $X(n)$, and $p_{i}$ represents the probability of $X(i)$, then the information entropy calculation formula of $X(n)$ is as follows:

$$H = -\sum_{i=1}^{n} p_{i} \log_{2} p_{i}$$

(4)

3.2. Kurtosis

Kurtosis is a dimensionless index, which is sensitive to impact characteristics, so it is often used to determine whether there is impact vibration fault in equipment. Normally, when the kurtosis index is around 3, there is no impact vibration problem. When this index is close to or more than 4, it indicates that the equipment has an impact vibration fault in operation. Calculation formula of kurtosis value:

$$C_{q} = \frac{1}{N} \sum_{i=1}^{N} \left( x_{i} - \bar{x} \right)^{4} / X_{rms}^{4}$$

(5)

The process of IMF component selection based on the combination of information entropy and kurtosis is defined as follows:

(1) Firstly, the information entropy of each IMF component is calculated and sorted according to the order from small to large;

(2) Calculating the kurtosis value of each IMF component, and take 4 as the reference index for screening;

(3) The IMF component with low information entropy and kurtosis value greater than or equal to 4 was selected by combining the two methods.

4. Experimental verification

In order to verify that the improved EMD method can suppress the endpoint effect and prove that the IMF component can be effectively used in fault diagnosis of rolling bearings, data from Case Western Reserve University were used for verification.

4.1. Test data

The data is from the bearing data center of Case Western Reserve University. The deep groove ball bearing with SKF6205 at the driving end is used. The inner ring fault test data are obtained under the condition that the speed is 1750r/min, the load is 2 horsepower and the fault diameter is 0.07 inches.

The failure frequency calculation formula of bearing inner ring is as follows:

$$f_{IR} = \frac{r / 60 \times n}{2} \left( 1 + \frac{d}{D} \cos \alpha \right)$$

(6)

The meanings of parameters in formula (6) are shown in Table 1.
Table 1. Bearing parameters.

| parameters                  | value |
|-----------------------------|-------|
| speed (r /min)              | 1950  |
| ball body                   | 9     |
| Roll diameter (d/mm)        | 7.94  |
| Section bearing diameter (D/mm) | 39.04 |
| Contact Angle (α/ angle)    | 90    |

The failure frequency of the inner ring of the bearing was calculated to be 157.94HZ.

4.2. Analysis of experimental results

4.2.1. Verify the endpoint effect inhibition effect of improved EMD. The experimental results are shown in Figure 3. By observing the waveforms at the image endpoints on the left and right sides of Figure 3, a comparison can be made to show that the improved EMD algorithm has a significant effect of endpoint effect suppressio

![Figure 3. IMF comparison chart of experimental data before and after extension.](image)

In order to further verify the effectiveness of the adaptive matching continuation algorithm, randomly selected part of the signal data the EMD decomposition, and analyze the results of Hilbert Huang (Hilbert - Huang Transform, HHT)[14] , the results of the analysis is shown in Figure 4 in the below diagram. The left is not using the adaptive matching continuation algorithm, on the right side is the results of the algorithm. By comparing the two endpoint time-frequency diagram in Figure 4, the conclusion is that before using the continuation algorithm, the divergent phenomenon is serious. After the extension, the divergence at the end points is effectively suppressed.
4.2.2. **Choose an effective IMF component.** The effective IMF component is selected by the method based on information entropy and kurtosis. According to the calculation results, the information entropy and kurtosis values of time-frequency distribution of each IMF component are shown in Table 2 and Table 3. The screening schematic diagram is shown in Figure 5 and Figure 6. In Figure 5, the part above the dotted line is the IMF component that meets the screening criteria; The IMF between the two dotted lines in Figure 6 is the IMF component that meets the screening criteria. On the left is the information entropy screening schematic diagram. On the right is the screening schematic diagram of kurtosis value. The kurtosis value takes 4 as the dividing line, from which IMF components with kurtosis value greater than or equal to 4 are selected, where IMF1 and IMF7 meet the requirements. Combining the two screening methods, IMF1 is the final screening case.

| IMF | IMF1 | IMF2 | IMF3 | IMF4 | IMF5 | IMF6 | IMF7 | IMF8 | IMF9 | IMF10 |
|-----|------|------|------|------|------|------|------|------|------|-------|
| entropy | 0.3283 | 0.1880 | 0.2698 | 0.4475 | 0.9258 | 1.5077 | 2.7156 | 4.4193 | 4.9751 | 2.6969 |

| IMF | IMF1 | IMF2 | IMF3 | IMF4 | IMF5 | IMF6 | IMF7 | IMF8 | IMF9 | IMF10 |
|-----|------|------|------|------|------|------|------|------|------|-------|
| kurtosis | 5.5473 | 3.5603 | 2.8626 | 3.2579 | 3.4750 | 4.0252 | 2.4576 | 1.9711 | 2.0998 |

4.2.3. **Feature extraction and fault determination.** Extracting the fault characteristics of IMF component after screening by envelope analysis and judge whether the equipment is malfunctioning according to the extracted fault characteristics. Figure 7 is the comparison diagram of IMF1 decomposition before and after the improvement based on EMD algorithm. It can be observed from the HHT envelope spectrum that the characteristic frequency of the inner ring fault of the bearing is 157.5HZ and the theoretical value is 157.94HZ, indicating that the screened IMF1 component can be used for the fault diagnosis of the bearing. The improved SNR is 0.1915, which is higher than 0.189 before the improvement, indicating that the fault diagnosis effect of EMD after the improvement is better than that before the improvement.
5. Conclusion
In this paper, the endpoint effect of EMD is suppressed by the adaptive matched waveform continuation algorithm, and the effectiveness of this algorithm is verified by the simulation signal and the randomly selected signal. Then the IMF component is screened based on the combination of information entropy and kurtosis value. Finally, the above methods are integrated to analyze the bearing data of Case Western Reserve University. The final test results show that the improved EMD algorithm can effectively suppress the endpoint effect and screen the appropriate IMF component. Moreover, the effectiveness in extracting bearing fault characteristics and diagnosing bearing faults has also been improved.

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