Bearing Fault Diagnosis Based on CEEMDAN and Teager Energy Operator

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Abstract. Aiming at the problem that the early shock signal of rolling bearing fault is weak and difficult to extract, a combination of CEEMDAN and Teager energy operator is proposed. Firstly, CEEMDAN decomposition and noise reduction are performed on the original signal, and the most sensitive component is selected according to the correlation coefficient criterion. Then the Teager energy operator is calculated on the component to extract the fault feature. The analysis of the outer ring and inner ring peeling fault signal of the steady speed rolling bearing results shows that the impact component signal can be effectively enhanced, the enhanced fault impact characteristics can be accurately identified from the interference, and the weak bearing fault characteristics can be extracted, which can effectively monitor and troubleshoot the rolling bearing.

1. Introduction
When the rolling bearing is seriously damaged, it will cause damage to the equipment, reduce the life of the equipment. Therefore, monitoring and fault diagnosis of the rolling bearing has great practical significance [1]. However, its early fault characteristics are weak, and it is difficult to extract under strong noise interference. To effectively extract this weak feature, one must suppress noise interference, and the second is to maximize the fault characteristics. Empirical Mode Decomposition (EMD) is an adaptive time-frequency signal processing method that can decompose nonlinear signals into a series of intrinsic mode functions (IMF) and filter the IMF components for noise reduction. It is widely used, but there is modal aliasing. [2] Ensemble Empirical Mode Decomposition (EEMD) method adds different white noise multiple times in the original signal, respectively performs EMD decomposition, and averages each IMF component to obtain the final IMF component. This method can improve the aliasing phenomenon of EMD algorithm to some extent, but the reconstruction error is related to the number of integration. Increasing the number of integration to reduce the error increases the amount of calculation and affects the computational efficiency. The Complete Ensemble Empirical Mode Decomposition with a-deptive noise (CEEMDAN) algorithm [3] adds a limited number of adaptive white noises at each stage of the EMD decomposition. Even in the case of less integration, the reconstruction error is almost zero, and the reconstructed signal is almost identical to the original signal, which not only solves the modal aliasing problem, but also ensures the computational efficiency. It has better adaptability to weak fault feature extraction. Literature [based on improved CEEMDAN - TKEO rolling bearing fault diagnosis method] [2] using CEEMDAN has achieved good results.

The Teager Energy Operator (TEO) is a nonlinear operator that estimates the total energy required to generate a dynamic signal from a signal source and enhances signal transient characteristics. It is ideal for detecting shock components in a signal. In recent years, many scholars have applied it to the
demodulation analysis of AM and FM signals, and achieved good application results \cite{4}, which is suitable for extracting transient shock characteristics in rolling bearing fault signals.

In order to effectively extract the weak impact characteristics of bearing faults, this paper studies the weak bearing fault feature extraction method combining CEEMDAN and Teager energy operators from two aspects: effective suppression of noise interference and enhancement of characteristic information. Taking the early pitting fault of transmission output shaft bearing as the research object, CEEMDAN is used to decompose the bearing vibration signal to obtain the IMF component, and then calculate the Teager energy envelope diagram of the most relevant IMF component to enhance the fault impact characteristics of the component, and identify the characteristic frequency to achieve early bearing fault diagnosis.

2. CEEMDAN algorithm principle

Torres et al. proposed CEEMDAN in 2011. The core of the method is to add white noise in a specific frequency band during the decomposition process, thereby solving the aliasing phenomenon that seriously affects the measurement results. The algorithm flow of CEEMDAN is shown in Figure 1:

![CEEMDAN Algorithm Flow](image-url)

Figure 1 CEEMDAN algorithm flow.
Specific steps are as follows:

1. Find $\overline{IMF_1}$, the expression is

$$\overline{IMF_1} = \frac{1}{l} \sum_{i=1}^{l} IMF_i$$  \hspace{1cm} (1.1)

2. Remove modal components from the original signal $\overline{IMF_1}$, thereby obtain the first margin signal $r_1(t)$

$$r_1(t) = x(t) - \overline{IMF_1}$$  \hspace{1cm} (1.2)

3. Then construct the set balance signal $r_i(t) + e_i E_i(N_0(t)), (i=1,2,...I)$, and decompose the aggregated signal to get $\overline{IMF_2}$

$$\overline{IMF_2} = \frac{1}{l} \sum_{i=1}^{l} (r_i(t) + e_i E_i(N_0(t)))$$  \hspace{1cm} (1.3)

4. For $k=1,2,...,K$, the calculation process is similar, first find the kth margin signal, and then find the k+1th IMF modal component $IMF_{k+1}$

$$r_k(t) = r_{k-1}(t) - \overline{IMF_k}$$  \hspace{1cm} (1.4)

$$\overline{IMF_{k+1}} = \frac{1}{l} \sum_{i=1}^{l} E_i(r_i(t) + e_i E_i(N_0(t)))$$  \hspace{1cm} (1.5)

5. When the pole of the margin signal $R_k(t)$ is less than 3, it will not be decomposed again and the algorithm terminates. The final decomposition result is

$$x(t) = \sum_{i=1}^{k} IMF_i + R_k(t)$$  \hspace{1cm} (1.6)

After the signal is decomposed, the IMK modal function is filtered and reconstructed according to the autocorrelation coefficient and the kurtosis value. Then the Teager energy operator is used for envelope demodulation, and the spectrum map is made to obtain the characteristic frequency peak.\footnote{\cite{5}}

### 3. Teager energy operator principle

The Teager energy operator is H. M. Teager's signal analysis algorithm when studying nonlinear speech modeling. Recorded as $\Phi$, with signal $x(t)$, then:

$$\psi[x(t)] = \left[\ddot{x}(t)\right] - x(t)\dddot{x}(t)$$  \hspace{1cm} (2.1)

Where $\ddot{x}(t)$ and $\dddot{x}(t)$ are the first and second order differentials of the signal $x(t)$ with respect to time $t$, respectively.

It has a linear undamped vibration system consisting of a mass of mass $m$ and a spring of stiffness $k$. The equation of motion is

$$x(t) = A \cos(\omega t + \varphi)$$  \hspace{1cm} (2.2)

Where $x(t)$ is the displacement of the mass relative to the equilibrium position, $A$ is the vibration amplitude, $\omega = (k/m)^{1/2}$ is the intrinsic (circle) frequency, and $\varphi$ is the initial phase. Then, at any time, the instantaneous total energy of the simple harmonic oscillator system is:

$$E = \frac{1}{2} k[x(t)]^2 + \frac{1}{2} m \ddot{x}(t)^2$$

Substituting $x(t)$ in formula (2.2) into equation (2.1) yields:

$$\psi[x(t)] = \psi[A \cos(\omega t + \varphi)] = A^2 \omega^2$$  \hspace{1cm} (2.4)

Comparing equations (2.3) and (2.4), it can be seen that there is only one coefficient $m/2$ between the output of the Teager energy operator and the instantaneous total energy of the simple harmonic motion, so that it can track the total energy required to generate a simple harmonic motion.

The signal energy in the traditional sense is defined as the square of the signal amplitude. If the impact amplitude is small, the impact component may be submerged by other components. The Teager energy operator output is the product of the instantaneous amplitude of the vibration and the square of the instantaneous frequency. Compared with the definition of the traditional energy, the product of the square of the frequency is increased, and the vibration frequency of the transient shock is higher. Therefore, the Teager energy operator output can effectively enhance the transient impact component.
4. Bearing fault diagnosis process based on CEEMDAN and Teager energy operator

The fault signal of the BJ2020S transmission output shaft bearing is collected. First, the CEEMDAN decomposition is applied to the fault signals of the outer and inner rings, and then the Teager energy operator is demodulated and analyzed. The specific process is shown in Figure 2:

```
Signal
  ↓
CEEMDAN Noise reduction
  ↓
IMF₁  ...  IMFᵢ  ...  IMF₆
  ↓
Select the largest component of the correlation coefficient
  ↓
Teager energy operator demodulation analysis
  ↓
Envelope spectrum
  ↓
get conclusion
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Figure 2 Bearing fault diagnosis process.

5. Diagnostic examples

5.1 Bearing signal acquisition

The object of this test is the BJ2020S transmission output shaft bearing. The structure of the test device is shown in Figure 3. The motor is used to simulate the engine to drive the transmission, and the generator is used to simulate the load. Without affecting the normal operation of the transmission, using the method of electric discharge machining, a point-like defect with length, width and depth of \(1.5\, \text{mm} \times 1.5\, \text{mm} \times 0.5\, \text{mm}\) is set on the outer ring of the bearing 50307E of the output shaft to simulate the peeling failure of the bearing outer ring; a point-like defect with a length, width, and depth of \(1.5\, \text{mm} \times 1.5\, \text{mm} \times 0.5\, \text{mm}\) is set on the inner ring of the output shaft bearing 6307N to simulate the peeling failure of the inner ring of the bearing. The specific parameter settings and fault characteristic frequencies of each fault bearing are shown in Table 1. The vibration sensor is used to acquire the radial position vibration signal of the output shaft housing of the transmission, and the speed sensor collects the input shaft speed signal. And when the signal is collected, the transmission is set to 2nd gear, and the input shaft speed is 923r/min. The sampling frequency is 40,000 and the sampling time is 1 s.
Table 1 Parameters of fault bearing setting.

| Fault status        | Bearing type | Characteristic frequency (Hz): $f_{	ext{Outer/F Inner}}$ |
|---------------------|--------------|----------------------------------------------------------|
| Outer ring fault    | 50307E       | 17.5/28.8                                                |
| Inner ring failure  | 6307N        | 20.4/32.5                                                |

5.2 Example of fault diagnosis of bearing outer ring peeling
For the analysis of the fault signal of the outer ring of the collecting bearing, the time domain diagram and the frequency domain diagram are respectively shown in Figure 4 and Figure 5, and the fault characteristic information cannot be seen from the figures.
Perform CEEMDAN noise reduction decomposition on the signal, set the number of decomposition layers to 6, and obtain the decomposition results as shown in Figure 6. The calculated correlation coefficients are shown in Table 2. The Teager energy operator demodulation analysis is carried out by selecting the component with the largest correlation coefficient. The envelope spectrum is shown in Figure 7. It can be clearly seen that the frequency is higher at 17.0HZ, 35.0 HZ, 52.0 HZ, and 70.0 HZ. Referring to Table 1, it corresponds to the outer ring fault frequency and its second, third, and fourth octaves. However, Figure 8 directly performs envelope demodulation analysis and cannot see the fault frequency.

**Figure 5 Original signal frequency domain diagram.**

**Figure 6 CEEMDAN decomposition noise reduction of the outer ring signal.**

**Table 2 Correlation coefficients of CEEMDAN components of the outer ring signal.**

| IMF1 | IMF2 | IMF3 | IMF4 | IMF5 | IMF6 |
|------|------|------|------|------|------|
| 0.892 | 0.563 | 0.442 | 0.389 | 0.409 | 0.224 |
5.3 Fault Diagnosis Example of Bearing Inner Ring Peeling
Perform CEEMDAN decomposition and noise reduction on the inner ring fault of the bearing, and set the number of decomposition layers to 6. The time domain diagram of each component is shown in Figure 9. The correlation coefficients of the respective components are shown in Table 3.
Figure 9 CEEMDAN decomposition noise reduction of the inner ring signal.

Table 3 Correlation coefficients of CEEMDAN components of inner ring signals.

| IMF1 | IMF2 | IMF3 | IMF4 | IMF5 | IMF6 | IMF7 |
|------|------|------|------|------|------|------|
| 0.910| 0.725| 0.543| 0.621| 0.318| 0.177| 0.103|

The IMF1 with the largest correlation coefficient is selected for the Teager energy operator demodulation analysis, as shown in Figure 10. It can be clearly seen from the figure that the frequency is higher at 32.2HZ and 64.5HZ. Referring to Table 1, it corresponds to the outer ring fault frequency and its double frequency. However, the envelope frequency demodulation analysis directly in Figure 11 does not show the fault frequency.

Figure 10 IMF1 component Teager envelope diagram of inner ring fault.
Figure 11 IMF1 component envelope spectrum of inner ring fault.

6. Conclusion

(1) CEEMDAN method can effectively suppress noise interference and improve signal to noise ratio; the Teager energy operator can effectively enhance the bearing's weak fault impact characteristics and highlight fault information.

(2) The combination of CEEMDAN and Teager energy operators can effectively extract the early fault characteristics of bearings.

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