Research on Fault Diagnosis of Gearbox Based on Acoustic Emission Signal Monitoring

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Abstract. For the problem of large noise interference in gearbox fault diagnosis and inaccurate time-frequency resolution of analysis signals, a method for analyzing acoustic emission signals using Hilbert-Huang transform method was proposed. Firstly, use the acoustic emission method to collect the fault signal of the gearbox, which reduces the interference of environmental noise. Then perform domain of time analysis on the single, and the time-frequency analysis was performed by short-time Fourier transform, wavelet transform and Hilbert-Huang transform. The results show that the Hilbert-Huang transform method is the best to analyze the acoustic emission signal, and the frequency of the fault can be analyzed accurately, and the time-frequency aggregation is accurate, which verifies the superiority of the method in gear fault diagnosis.

1 Introduction

During the mechanical operation, the gears of the core components of the transmission are in a harsh environment with high temperature, heavy load and periodic operation for a long time. When the working time is accumulated to a certain extent, the reliability of the gear operation is poor. In order to ensure personal safety, reduce downtime and maintenance time, and improve work efficiency, equipment failures must be discovered in time. Acoustic emission (AE) [1] has a wide range of applications because of its high detection frequency [2] and its ability to be detected online.

Xihui Liang et al. from Canada [3] proposed a modified Hamming function to represent the influence of multiple vibration source transmission paths, and analyzed the vibration signals that are obtained by combining the vibration sources, the fault symptoms of the gear cracks are identified finally. Jinglong Chen et al. from China [4] used the empirical wavelet transform to decompose the signal on the basis of orthogonality to extract the inherent fault features and they used the wavelet spatial domain coefficients for threshold denoising, thereby improving the signal-to-noise ratio. Heidari et al. from America [5] proposed a scale selection criterion based on the maximum relative energy and analyzed the optimal decomposition scale of wavelet. Then the wavelet coefficient is combined with other parameters as the input of the classifier. The experimental results showed that the method is more effective in diagnosing gearbox failure. Muhammet Unal et al. from Turkey [6] analyzed the envelope extraction feature extraction method of Hilbert-Huang transform and Fourier transform, and
combined with neural network to propose an optimized fast response network structure. However, the above research was based on mechanical vibration signals, and the acoustic emission signal has high sampling frequency and strong anti-interference ability. There are relatively few researches on the use of acoustic emission signals to detect gearbox fault diagnosis, so it has research value. This study is based on the acoustic emission detection method to study the gearbox fault signal, and analyzes the advantages and disadvantages of several time-frequency distributions. A method of Hilbert-Huang transform based on acoustic emission signals is proposed.

Diagnosing the gearbox failure can be divided into the following steps: Firstly, the acoustic emission signal is collected from the gearbox using an acoustic emission detection instrument. Then the signal is processed using a suitable algorithm [7] to extract the fault characteristics. Finally, the extracted fault features are compared with the inherent fault characteristics of the experimental equipment to achieve the purpose of diagnosing the fault.

2. Introduction of acoustic emission and time-frequency analysis methods

2.1 Principle and characteristics of acoustic emission

When subject to internal force or external force to an object, it will deform. The phenomenon that the energy is released in a short time to form an elastic wave is called an acoustic emission phenomenon. Its sampling frequency is high, generally in the range of 50Khz-3Mhz, and the sampling frequency of the vibration signal is generally lower than 10Khz, which is in the same frequency band as the ambient noise, which makes the vibration signal susceptible to noise, and the sampling frequency of the acoustic emission signal is high, anti-interference ability is strong, can filter out environmental noise at low frequency. In addition, the acoustic emission signal is released actively by the damaged object without the need to provide energy by the detecting device, and the presence of the fault can be detected at the initial stage of the fault, which makes the detection efficiency higher. The acoustic emission signal is captured by the sensor after being emitted by the detection object, amplified by the preamplifier and transmitted to the acoustic emission collection box, and the data is transmitted to the computer finally. The schematic diagram shows in Figure 1.

![Figure 1. Schematic diagram of acoustic emission propagation](image)

2.2 Time-frequency analysis method and principle

2.2.1 Short-time Fourier transform principle (STFT). First, introduce the Fourier transform, a weighted summation form of a standard function formed by expanding a function $z(u)$ that satisfies the absolute integrability condition in the real number field. The formula is as shown in (1):

$$FT[z(u)] = \int_{-\infty}^{\infty} z(u) e^{-j2\pi fu} du \quad (1)$$

Fourier is based on different sine waves, which are superimposed on each other through countless bases. After transformation, the frequency domain information can be analyzed clearly, but the Fourier transform can only observe the frequency and can’t observe the time information. It is a good analytical tool for stationary signals, but it cannot be used as an analytical method for non-stationary signals. The principle of the short-time Fourier transform method is to convolve a window function with the original Fourier transform function. The calculation formula is as follow equation:
\[ \text{STFT}_g (t, f) = \int_{-\infty}^{\infty} z(u) g(u-t) e^{-j2\pi fu} du \quad (2) \]

g(t) represents the window function, the window function can perform time displacement and frequency shift, so the short-time Fourier transform has local time-frequency characteristics, but the window function g(t) is a fixed value, measured by Heisenberg[8]. The effect of the principle is not allowed to be limited when analyzing non-stationary signals. When the frequency of the signal is high, the spectrum is blurred.

2.2.2 Wavelet Analysis (WT) Principle. Different from the Fourier transform, which uses a sine wave as the basis, the wavelet transform can select the appropriate wavelet base and automatically "zoom" according to the frequency component of the actual signal. The time-frequency resolution varies with time scale. The wavelet transform began with the proposed wavelet normalized basis proposed by Haar in 1910. The scholar Morlet concluded that the traditional Fourier transform method is difficult to meet the requirements of analyzing the local characteristics of seismic waves in 1982, and the concept of wavelet is proposed for the first time. The mother wavelet is stretched and moved on the time axis to get:

\[ \varphi_{a,b} (t) = |a|^{1/2} \varphi\left( \frac{t-b}{a} \right) \quad (3) \]

Where a is the scale factor, b is the translation factor, and a>0. The wavelet transform formula is as shown in equation (4):

\[ \varphi^{*} (t) = \varphi^{*}\left( \frac{t-b}{a} \right) W_T (a,b) = |a|^{1/2} \int_{-\infty}^{\infty} \varphi\left( \frac{t-b}{a} \right) \]  

\[ \left( t-b \right) \right) dt \quad (4) \]

\[ \varphi^{*} (t) \text{ represents the conjugate complex number of } \varphi (t) \]

The time-frequency resolution of the wavelet can be changed according to the analysis signal. When analyzing the low-band signal, the window of time is wide and the resolution of time is low, the frequency resolution is high. when it is for high-band signals, the window of time is narrow, the resolution of time is high, and the frequency resolution is low. Its principle is to use a series of functions to represent or approximate a signal. This series of functions is called a wavelet function system. The wavelet transform is composed of different size expansion and translation transformations of this basic wavelet function, so that the wavelet function employs different resolutions in the normal signal of the gear and the shock signal of the worn gear.

2.2.3 Hilbert-Huang Transform (HHT) Principle. EMD (empirical mode decomposition) and Hilbert spectrum of time are collectively referred to as HHT, which is divided into two steps. The first step is to use EMD method to decompose the signal into several IMFs (inherent modal functions). The second step is to perform a Hilbert transform on each IMF component to obtain the instantaneous frequency and the instantaneous amplitude, thereby obtaining a time-frequency distribution graphics.

(1) Necessary conditions of the IMF
   a. The extreme point of the curve in the signal are equal with zero point or most different no more than one.
   b. At any point of the signal curve, the mean value of the maximum and minimum extreme points of the envelope is zero and the signal is locally symmetrical about the time axis.

(2) EMD principle
   The input signal x(t) finds the local maximum extreme point and the minimum extreme point of the signal that all meet the conditions firstly. Then use the cubic spline function to interpolate all the maximum point and minimum points one by one. The upper and lower envelopes are obtained, and the above method is continuously used to obtain N IMFs components finally.

\[ x(t) = \sum_{i=1}^{n} c_i + r_i \quad (5) \]
\( c_i(t) \) represents an eigenmode component, and \( r_i \) represents a residual component.

(3) Calculate Hilbert Spectrum

Hilbert transform for each IMF component of the above formula, obtain

\[
H[c_i(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{c_i(t)}{t-\tau} d\tau
\]  

(6)

Then constructing an analytical signal:

\[
Z_i(t) = c_i(t) + jH[c_i(t)]
\]  

(7)

Finally, obtained the Hilbert spectrum, it is:

\[
H(w,t) = \text{Re} \sum_{n=1}^{n} a_i(t) e^{j\int w_i(t) dt}
\]  

(8)

\( \text{Re} \) represents the real part, \( a_i(t) \) represents the instantaneous amplitude function, and \( w_i(t) = \frac{d\theta}{dt} \) represents the instantaneous frequency.

Since there is no constant prior substrate, the signal is adaptive when it is decomposed. It can change its instantaneous frequency and instantaneous amplitude, and improve the efficiency of signal decomposition. Therefore, EMD is suitable for analyzing the impact signal of gear fault. The window size in the short-time Fourier transform method cannot be changed, and the time-frequency resolution of the wavelet transform can be changed according to the signal frequency. However, there are many disadvantages such as selecting wavelet base are difficult, Fixed base function, constant multi-resolution, etc. Wavelet transform lacks adaptability, and Hilbert-Huang transform has adaptability, Therefore, it is better to analyze the acoustic emission of the gearbox in this way.

3. Experimental analysis

3.1 Experimental device and parameter settings

The JZQ250 reducer, which has been working for nearly 5,000 hours, is suspected of having a fault, so the gearbox was tested. The experimental equipment includes: motor, signal amplifier, SAEU2S acoustic emission signal collection box, computer, etc. The number of teeth of the reducer large gear is 85, the number of teeth of the small gear is 14, the motor is 1500 W, 1400 r/min, the pulley is connected between the motor and the first speed reducer, the diameter of the motor connection key is 8 cm, and the reducer is connected. The diameter of the key is 12 cm, the reduction ratio of the pulley is 1.5, and the reduction ratio of the primary reduction gear is 6. Using SAEU2S software and detection system, the sensor model is SR150M, the preamplifier type is PA I wideband, the transmission gain is 40 dB, the data acquisition card is SAEU2, and the USBAE signal analysis software is installed on the computer. Board setting: sampling frequency 4.5M Hz, sampling length 8192, pinion rotation frequency 15.6 Hz, large gear rotation frequency 2.6 Hz, meshing frequency 218 Hz, apply proper amount of coupling agent between sensor and gear box. The experimental setup is shown in Figure 2.

![Figure 2. Gearbox fault detection device diagram](image)
3.2 Experimental data and results analysis

The experiment collected a total of 15,000 acquisition points, the sampling time is about 1.8s, forming a modulation signal, there will be obvious impact signal generated every 3300 collection points, the time domain diagram shown in Figure 3, the initial judgment of the gearbox has the fault exists.

By performing the short-time Fourier transform on the fault signal, it can be seen that there are five equally spaced pulses near the 200k-1M hz frequency band, but the time-frequency resolution is low and the fault characteristics are blurred. When the window of time is narrow, its frequency resolution is low greatly, the spectrum is blurred, and the fundamental frequency and the oscillation frequency have intersections. The time-frequency analysis diagram is shown in Figure 4. When the window of time is wider, the domain of time resolution is low, and the time-frequency diagram is still blurred. In short words, Fourier cannot satisfy the non-stationary signal well. It can not show a clear time-frequency diagram.

Figure 3. Waveform of the acoustic emission signal

Figure 4. Short-time Fourier transform time-frequency diagram

Figure 5 shows the wavelet time-frequency analysis of the acoustic emission signal during the operation of the gearbox. There are 5 frequency bands with brightness concentration in 15000 acquisition points. The frequency of the impact is about 2.6 hz, which is close to the frequency of the large gear. The frequency bands are mainly concentrated in 200k-1M hz, which is higher than the resolution of Figure 4. Both the domain of time analysis and the frequency domain analysis are much better than the short-time Fourier transform.
The Hilbert-Huang transform method was introduced, and the time-frequency analysis of the collected acoustic emission signals was performed by this method. This is the method used in a new occasion. It can be seen from Fig. 6 that the frequency has a significant impact component near the 100kHz-800kHz frequency band. A total of 5 impacts occurred in 15,000 collection points, and the number of collection points was approximately 3300 points. The time interval of the impact component is 0.4 s, which is close to the gearbox’s large gear rotation frequency of 2.6 hz. It can be considered that the large gear of the gearbox is faulty. Moreover, the time-frequency distribution diagram has frequency bands clearly and aggregation strongly. Compared with the wavelet transform method, the short-time Fourier transform method and the Hilbert-Huang transform method, we can see that the Hilbert-Huang transform method compare with the short-time Fourier analysis method and the wavelet transform are better, the frequency band is more obvious and more adaptive.

Disassemble the gearbox for observing, as shown in Figure 7, it is found that there is indeed tooth wear on the large gear, verifying the reliability of the method we proposed.
4. Conclusion

(1) The frequency of the signal collected by the vibration acquisition method is low relatively, it is in the same frequency band as the ambient noise, and the noise interfere strongly. Compare with the signal collected by acoustic emission, have the characteristics of anti-interference ability strongly and the sampling precision is high, and early micro fault information can be found. Therefore, the method of use acoustic emission signals to detect gearbox failures is better than vibration signals.

(2) For the classic Fourier transform can not be used to analyze the impact of the signal, short-time Fourier transform method time-frequency resolution is not precisely, wavelet transform method have the shortcoming of select wavelet base difficult, basis function fixed and others, the introduction of Hilbert-Huang transform method is used to process the acoustic emission signal of the gearbox. The time-frequency analysis of the signal is performed by wavelet transform, Hilbert-Huang transform and short-time Fourier transform respectively. The results showed that better results can be obtained by using the Hilbert-Huang transform method.

5. References

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