Research on Gear Signal Fault Diagnosis Based on Wavelet Transform Denoising

Yuan Li 1,2, Zhuojian Wang 2, Zhe Li 2* and Hao Li 1,2
1 Graduate School, Air Force Engineering University, Xi’an, China
2 Aeronautics Engineering College, Air Force Engineering University, Xi’an, China
*E-mail: k852665378@afeu.cn

Abstract. As an important part of modern machinery, gears are safe and reliable directly related to the normal operation of the mechanical system, and when the gears are abnormal, it is very important to carry out fault diagnosis in time and effectively. Wavelet transform is effective in signal time-frequency analysis and fault diagnosis. Based on the wavelet analysis method, this paper first filters and de-noises the vibration signal data of a certain type of gear, and then performs fault analysis. Time-frequency analysis of time-domain signals has a better effect on gear fault diagnosis.

1. Introduction
Wavelet analysis should be extensive in filtering and denoising. Zou Xinlei [1] et al. used the frequency domain filtering method in view of the large amount of noise in airborne gravity data and proposed a FIR low-pass filtering method suitable for airborne gravity data. The results show that the filtering effect of this method is obvious. Hu Zheng et al. [2] constructed a new wavelet basis function, which aims to solve the intermittent impact noise in engine noise, which can characterize engine failures, and successfully realized the extraction and diagnosis of motorcycle engine failure features. Zhang Xudong [3] compared the denoising effects of Fourier transform and wavelet transform in seismic data, and found that wavelet transform has better denoising effect on data, and wavelet transform has more obvious advantages when analyzing data with singular values. Through the above research results, it can be found that wavelet transform has obvious advantages in noise reduction and time-frequency analysis of signals. Based on wavelet transform, this paper diagnoses gear faults, and proposes a gear fault diagnosis method based on wavelet analysis.

2. Basic theory
2.1. Principle of Wavelet Analysis
Wavelet transform is a family generated by basic wavelets through scaling and translation. This family is called wavelet. Its expression is shown in formula (1):

$$\Psi_{a,b}(t) = a^{\frac{1}{2}}\Psi\left(\frac{t-b}{a}\right)$$

(1)

Where $a$ is the scale parameter and $b$ is the position parameter. Then for a one-dimensional signal $y(t)$, its wavelet transform is:

$$W(a,b) = a^{\frac{1}{2}}\int_{-\infty}^{\infty} y(t)\Psi^*\left(\frac{t-b}{a}\right)dt$$

(2)
Then the position parameter $b$ in equation (2) is transformed by Fourier transform:

$$\widehat{W}_\epsilon(a,b) = \sqrt{a} y(\omega) \widehat{\Psi}(a,\omega)$$

(3)

It can be seen from formula (2) that the difference between wavelet transform and Fourier transform lies in the difference of basis function. The basic principle of wavelet transform is to decompose the signal into sub signals with different frequency bands by using the basis function $\psi_{a,b}$. In wavelet decomposition, the original signal $y(t)$ is decomposed into approximate signal and detail signal by given basis function. The approximate signal represents the low frequency part of the original signal $y(t)$, and the detail signal represents the high frequency part of $y(t)$. Then the detail signal is decomposed according to the number of decomposition layers. Its decomposition structure is shown in Figure.1.

![Figure 1. Structure of wavelet decomposition](image)

After wavelet decomposition, the approximate coefficients and detail coefficients of each scale are obtained, and then the signal is reconstructed after wavelet coefficient processing to achieve the purpose of wavelet analysis. It can be seen that wavelet analysis is a signal analysis method with almost no loss [4].

### 2.2. Principle of wavelet filtering and denoising

In practical engineering applications, the signals analyzed are not all linear signals, and most of them contain noise. The typical one-dimensional signal model with noise can be expressed as [5]:

$$s(t) = f(t) + \sigma \cdot e(t) \quad t = 0, 1, \cdots, n$$

(4)

Where $f(t)$ is the original signal, $f(t)$ is the noise free signal, $e(t)$ is the noise signal, and $\sigma$ is the noise standard deviation. The useful signal is usually low frequency signal, relatively stable, and the noise signal is high frequency signal. Using wavelet to decompose the noisy signal, the high-frequency wavelet coefficients often represent the noise signal. Useful signal and noise signal often show different properties in wavelet transform, so denoising methods can be divided into modulus maximum reconstruction denoising, spatial correlation denoising, wavelet threshold denoising, and the most commonly used method is threshold denoising [6]. A complete wavelet denoising process can be shown in Figure 2.

![Figure 2. Wavelet denoising process](image)
As can be seen from Figure 2, when de-noising, the noisy signal is preprocessed first, and the appropriate wavelet basis and the corresponding decomposition layers are selected. Then the high-frequency coefficients of wavelet decomposition are quantized by threshold, and the high-frequency coefficients of each layer are quantized by threshold. Finally, the signal is reconstructed according to the wavelet decomposition layers and the high-frequency and low-frequency coefficients. There are usually two parameters $\text{SNR}$ (signal to noise ratio) and $\text{MSE}$ (minimum mean square error) to evaluate the effect of signal denoising:

$$\text{SNR} = 10 \cdot \log_{10} \sum_{i=1}^{N} \left( \frac{y_i^2}{x_i - y_i} \right)$$  \hspace{1cm} (5)

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} (y_i - x_i)^2$$  \hspace{1cm} (6)

For the evaluation index of wavelet de-noising quality, Zhu Jianjun [7] introduced the concept of root mean square error and smoothness of alternative parameters, and the evaluation results are more accurate. In order to facilitate calculation, this paper still selects the evaluation index of signal-to-noise ratio and mean square error.

3. Mechanical gear signal analysis

The main characteristics of mechanical gear transmission are high mechanical efficiency, long service life, high reliability and compact structure. It is usually used with other gears. In the fault diagnosis of this wheel, the vibration signal is usually measured, the time-frequency analysis is carried out, the fault characteristic frequency of the gear is obtained, and then the fault reason is analyzed.

In this experiment, the vibration signal of a gearbox is collected, and two groups of tests are carried out on the fault gear and the normal new gear respectively. Five acceleration sensors (five channels) are used in the test. The driving bevel gear is driven by the tester to run at 500 r/s. The sampling frequency of the test system is 20 kHz and the sampling time is one second. At this point, the characteristic frequency of the driving bevel gear is $f_c=8.33Hz$. The corresponding relationship is shown in Table 1.

| Gear (500r/s) | $f_r$ (Hz) | $f_c$ (Hz) |
|--------------|------------|------------|
| Driving bevel gear | 8.33 | 200 |

$f_r$ is the rotation frequency and $f_c$ is the meshing frequency.

In the test analysis, five channels of data are collected, and 20000 data points are collected in one second for each channel. In order to show which channel reflects more real gear vibration signal, the autocorrelation analysis of the data of the five channels is carried out. The results show that the frequency components of the three channels are less and there are obvious periodic test points. Therefore, the signal analysis selects three channel data to realize the signal noise reduction and fault analysis.

4. Simulation experiment

4.1. Evaluation of denoising effect

The effect of threshold filtering denoising is usually related to the selected threshold, which is usually related to the selected threshold. In the experiment, five thresholds are selected to denoise the vibration signal, and the evaluation effect is shown in Table 2.

| Approach       | SNR      | MSE    |
|----------------|----------|--------|
| Forced denoising | 94.9812  | 0.3123 |
In the experiment, the selected wavelet base is db2, and the number of decomposition layers is three. From the evaluation effect, the default hard threshold and Stein estimation soft threshold denoising effect is better (the larger the $SNR$, the smaller the $MSE$, the better), but in terms of the smoothness of denoising, Stein estimation soft threshold denoising is better. On this basis (Stein estimation soft threshold denoising, db2 wavelet basis), we continue to study the influence of the number of decomposition layers on the denoising effect. The calculation results are shown in Table 3.

| Decomposition layer | SNR      | MSE     |
|----------------------|----------|---------|
| 3                    | 102.3318 | 0.1361  |
| 4                    | 105.1005 | 0.1415  |
| 5                    | 102.8586 | 0.1419  |

According to the data analysis in the table, the denoising effect is better when four layers are decomposed. Therefore, the db2 wavelet basis is selected, and the Stein Unbiased Estimation threshold is used to decompose the four layers to filter and denoise the gear signal.

4.2. Failure analysis of wavelet gear signal

Many faults of bearings and gears are generally characterized by impact. For the impact in various cases, the following wavelet basis db5 is more suitable for the extraction of impact features [8]. In the wavelet analysis of gear signal, db5 wavelet is selected to decompose and reconstruct the original 20000 signal points in 8 layers, and then the coefficients of each layer are transformed by fast Fourier transform to analyze the spectrum features, Then the fault characteristics of gear are analyzed. In order to compare the fault characteristics, the fault gear and normal gear are tested in the experiment.

![Figure 3. Approximate coefficient of the 8th layer of normal gear](image)
Figure 4. Detail coefficient of 5th and 6th layers of normal gear

Figure 5. Approximate coefficient of the 8th layer of the fault gear

Figure 6. Detail coefficient of 5th and 6th layers of fault gear

The approximation coefficient represents the low frequency part of the signal, while the detail coefficient represents the high frequency part of the signal. After the fast Fourier transform of the reconstructed signal of the approximate coefficient and the detail coefficient, the low frequency and
high frequency of the signal can be analyzed. For normal gears, as shown in Figure.3 and Figure.4, the frequency spectrum of the detail coefficient reconstruction signal of the eighth layer can be found to be approximately 1, 2 and 3 times of the rotation frequency (8.33Hz), and the engagement frequency (200Hz) corresponding to the engagement frequency (200Hz) of the active bevel gear can be found in the detail signals of the fifth and sixth layers. In the spectrum analysis of normal gears, it can be found that the characteristic frequency is the integral multiple of gear characteristic frequency.

It can be found in Figure.5 and Figure.6 that the frequency spectrum of the signal reconstructed by the 8th approximate coefficient of the fault gear shows that the frequency of the rotation of the active bevel gear is 1/2, 1, and 1.5 times, that is, the high amplitude vibration of 0.5 times and 1.5 times frequency is generated near the speed frequency of the gear, and the basic frequency band of rotation speed is also provided on both sides. The first, first and second frequencies of the engagement frequency of the active bevel gear are found in the detail signals of the 5th and 6th layers. Through the analysis of the above characteristic frequency, it can be concluded that the gear failure occurs when the gear breaks down or the tooth breaks down, which leads to the high vibration amplitude near the base frequency.

5. Conclusion

Based on the wavelet analysis method, this paper analyzes and diagnoses the gear mechanical vibration signal. The main work is as follows:

(1) The selection of the relevant threshold of wavelet denoising and the influence of the number of wavelet decomposition layers on the denoising effect are studied. The results show that the Stein unbiased estimation threshold is selected and the denoising effect is better when the 4 layers are decomposed.

(2) Through the 8-layer wavelet decomposition of the vibration signal after denoising, and comparing the frequency spectrum analysis of the faulty gear and the normal gear, it is finally concluded that the fault of the gear is a broken tooth or a cracked tooth.

Through the analysis and diagnosis of the vibration signal of the fault gear, the fault type can be accurately judged, which provides an effective basis for the subsequent maintenance work. And the current work is only to diagnose the single fault that has appeared at this stage. The next step is to realize the synchronous diagnosis of different faults and improve the diagnosis efficiency.

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