Vibration signal Processing of Cutting Gearbox Based on Haar-Wavelet Denoise

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Abstract. Cutting gearbox with complex structure is difficult to obtain mechanical parameters and conduct fault diagnosis, aiming at this problem, a novel handling method is proposed after studying vibration theory of gearbox. Firstly, traditional calculation method and modal analysis are combined to acquire mechanical parameters of gearbox, especially inherent frequencies of decelerator housing and gear transmissions which are difficult to calculate. Based on Haar-Wavelet, vibration test signal of cutting gearbox is de-noised. And Fast Fourier Transform (FFT) is conducted for de-noised signal, thus operation status of gearbox can be analyzed in time domain and frequency domain. Taking a mine cutting gearbox as an example, the method proposed is used to detect parts damage in maintenance process. It is found that the tooth surface of second-stage gear transmission arise even wear, and this is consistent with actual situation. Therefore the practicability and effectiveness of this method are verified, and a new solution is provided for other gearboxes with complex structure.

1. Introduction
As key component to bear load and transmit power, gearbox is widely used in production. With the development and application of computer aided design, researchers can ensure performance of gearboxes in the design stage for multi-stage transmission gearboxes with complex structure. However, in next sessions such as components production, gearbox assembly, and application in equipment would generate irreversible degradation for gearbox performance, this may lead to real performance is inconsistent with the design performance of gearbox. Some studies have shown that the intensity of vibration and noise generated by mechanical equipment under dynamic conditions as well as its main frequency are closely related to the type, degree, location, and reason of failure of gearbox [1]. Therefore, how to obtain mechanical characteristic parameters of the multi-stage gearbox and diagnose its operation state using vibration signals obtained from vibration test are key problems to be solved urgently in the process of acceptance inspection and maintenance.

In the aspects of obtaining mechanical parameters and dealing with vibration signals, many researchers have conducted studies. In order to get mechanical characteristic parameters of gearbox, especially inherent frequencies of every gear transmission and the gearbox housing, Wang Feng [2] and Li Yafeng [3] established the finite element models of herringbone gear box and gear box of draught fan respectively in ANSYS software, and they obtained inherent frequencies and corresponding vibration modes of the system by conducting modal analysis. Qian Lulu [4] et al. got the inherent frequency of single-stage gear transmission system by establishing the dynamic model, and they compared the results with those obtained by establishing finite element model. Weis Peter [5]
et al. used Workbench software to carry out modal analysis for gearbox housing, and the inherent frequency of gearbox housing with load was obtained. He Zeyin [6] et al. developed a coupled gear-rotor-bearing-housing system, and the mode of vibration as well as modal frequency is obtained.

In addition, Puchalski Andrzej [7] tested vibration acceleration signals to diagnose internal combustion engine faults online and offline, respectively. Afia Adel et. al. [8] performing autogram to handle signal, and Fourier transform is applied to extract the fault signature. Sun Ruobin [9] et al. conducted dynamics simulation to obtain the prior information of a chipped planetary gear set, and utilize the information in the time domain analysis. Fang Yuan [10] et al. analyzed vibration signal of electric vehicle power system by means of spectrum analysis, which provided experimental support for the optimal design of power system. Dong Lei [11] et al. applied local mean decomposition (LMD) to decompose vibration signals of the hoist spindle system. When conducting bearing fault diagnosis, Goncalves, Mario J. M. [12] et al. used various methods to deal with vibration signals of motor bearings, and results were compared. Formberger Max [13] and others collected angular displacement of axle in gearbox and diagnosis it.

A combined method to handle vibration test signals is proposed in this paper. Vibration mechanism of the cutting gearbox is researched, and frequency components of vibration signal as well as signal characteristics corresponding to gearbox fault are analyzed. Then taking a mine cutting gearbox with complex structure as an example, inherent frequencies of gearbox housing and every gear transmission are obtained. In addition, other mechanical parameters of cutting gearbox are calculated by traditional formulas. Finally, vibration test of the gearbox is carried out in maintenance stage. Based on Haar-Wavelet de-noised method, time-domain vibration signal is handled. And then the method of Fast Fourier Transform is conducted to the signal, thus performance of cutting gearbox and damage of the original parts can be diagnosis from both time-domain and frequency-domain perspectives.

2. Vibration mechanism of cutting gearbox

Vibration signal of mine gearbox is complex, especially for planetary gearboxes, they will excite highly modulated vibration [14]. Aiming at multi-stage cutting gearbox with planetary gear transmission, its vibration is usually affected by varieties of factors and it will also be influenced by cross-modulation. If the cross-modulation component in test signal is neglected, the vibration signal can be shown in equation (1):

\[
Y(t) = G(t) + \sum X_K(t)D_E(t) + \sum X_{GA}(t)D_G(t) + \sum X_X(t)D_G(t) + \sum X_B(t)D_B(t) + n(t)
\]

In the equation, \(G(t)\) is vibration component produced by rotating frequency of axes; \(\sum X_K(t)D_E(t)\) is modulation signal result from meshing frequencies of every gear transmission; \(\sum X_{GA}(t)D_G(t)\) is modulation signal result from inherent frequencies of every gear transmission; \(\sum X_X(t)D_G(t)\) is modulation signal result from inherent frequency of gearbox housing; \(\sum X_B(t)D_B(t)\) is signal component produced by abnormal vibration of rolling bearing; \(n(t)\) is other interference signal; \(X(t)\) is carrier signal; \(D(t)\) is modulation signal.

If there is no fault and tooth profile error is slight in gearbox, the trend of vibration signal would be relatively stable, and there is no obvious shock phenomenon. If gear transmissions in gearbox exists serious faults such as broken gear teeth and serious teeth profile error, it will lead to violent vibration. And it not only may appear modulation phenomenon result from gear meshing frequency, but also may cause resonance phenomena. Hence, it can be found that there is side-band near inherent frequencies of gear transmissions with fault in frequency spectrum. When more serious faults occur in cutting gearbox, it may generate large energy and cause resonance phenomena of gearbox housing. And it can be found that there is side-band near inherent frequency of gearbox housing in frequency spectrum. Furthermore, if rolling bearings are damaged and produce abnormal vibration, the phenomenon of modulation will appear and side-band would occur near the inherent frequency of rolling bearing with fault, and modulation signal are passing frequencies.
3. Obtaining mechanical parameters of cutting gearbox
Before handling vibration test signal, mechanical parameters of cutting gearbox should be obtained. Based on these parameters, cutting gearbox can be diagnosed combined with frequency spectrum. Traditional formulas and modal analysis are combined in this paper. On the one hand, formulas are used to calculate rotation frequencies of axles, gear meshing frequencies and others, on the other hand, modal analysis can be conducted to calculate inherent frequencies of every gear transmission and gearbox housing. The following will introduce how to obtain mechanical parameters of cutting gearbox in detail.

3.1. Obtaining mechanical parameters through formulas
Assuming that the speed of an axle in gearbox is \( n \) (r/min), the number of gear teeth on this axle is \( z \), and rotation frequency of this axle can be calculated by equation (2):

\[
f_n = \frac{n}{60}
\]  
(2)

The meshing frequency of the gear can be calculated as follows:

\[
f_z = z \cdot f_n = z \cdot \frac{n}{60}
\]  
(3)

In addition, passing frequencies of rolling bearings need to be calculated, and specific formulas are as follows:

Passing frequency of inner ring:

\[
f_i = \frac{1}{2} mf_n \left( 1 + \frac{d_0}{D} \cos \alpha \right)
\]  
(4)

Passing frequency of outer ring:

\[
f_o = \frac{1}{2} mf_n \left( 1 - \frac{d_0}{D} \cos \alpha \right)
\]  
(5)

Passing frequency of bearing ball:

\[
f_g = \frac{1}{2} mf_n \left[ 1 + \left( \frac{d_0}{D} \cos \alpha \right)^2 \right] \frac{D}{d_0}
\]  
(6)

Passing frequency of bearing retainer:

\[
f_b = \frac{1}{2} mf_n \left[ 1 + \left( \frac{d_0}{D} \cos \alpha \right)^2 \right]
\]  
(7)

In above formulas (4) to (7), \( m \) is the number of bearing ball, \( d_0 \) is the diameter of bearing ball, \( D \) is the diameter of bearing, and \( \alpha \) is the contact angle.

3.2. Obtaining inherent frequencies by conducting modal analysis
3-D models are built for gearbox housing and every gear transmission, which are difficult to get inherent frequencies. And then these models are imported to Workbench software to conduct modal analyses in this study. Because stiffness of structure will be affected by stress generated by load, in order to make the simulation result more realistic, pre-stressed modal analyses are conducted to gearbox housing and each gear transmission to obtain their inherent frequencies. The specific analysis process and results are described in detail as follows.

It is necessary to perform static analysis to obtain stress distribution firstly when mechanical structure needs to conduct pre-stressed modal analysis. The solid model of gearbox housing built in
Solidworks is imported into Workbench software, and material parameters are set. Meshing model can be built using free mesh method as shown in figure 1.

![Meshing model of decelerator housing.](image)

**Figure 1.** Meshing model of decelerator housing.

According to work condition when conducting vibration test to gearbox housing, boundary condition is set for meshing model, and then static analysis is performed. After static analysis is completed, modal analysis is performed to obtain inherent frequencies and corresponding vibration diagram. Vibration diagram of first-mode is shown as figure 2, and inherent frequencies of first six modes are shown in table 1.

![Vibration diagram of first mode.](image)

**Figure 2.** Vibration diagram of first mode.

| Mode | Frequency/Hz |
|------|--------------|
| 1    | 56.32        |
| 2    | 56.48        |
| 3    | 75.64        |
| 4    | 95.00        |
| 5    | 95.14        |
| 6    | 137.84       |

**Table 1.** Inherent frequency of decelerator housing.

In addition, modal analyses are performed to every gear transmission refer to above process in turn. And their inherent frequencies are shown in table 2.

| Mode | Frequency/Hz |
|------|--------------|
|      | Frist stage  | Second stage | Third stage | Fourth stage | Fifth stage |
| 1    | 166.44       | 89.57        | 41.91       | 52.49        | 39.82       |
| 2    | 208.77       | 102.38       | 51.99       | 82.61        | 52.73       |
| 3    | 528.10       | 587.36       | 648.24      | 469.27       | 405.26      |
| 4    | 805.70       | 814.53       | 752.34      | 641.48       | 721.34      |
| 5    | 1099.45      | 981.58       | 972.51      | 883.47       | 903.24      |
| 6    | 2961.1       | 1685.3       | 1288.4      | 1095.6       | 1249.1      |

**Table 2.** Inherent frequency of gear drive.

Therefore, cutting gearbox can diagnosed via de-noised signal from vibration test based on these mechanical parameters calculated from formulas and obtained from modal analysis.
4. Dealing with vibration signal of cutting gearbox

Conducting vibration tests to mining gearboxes, it is necessary to arrange measuring points at input, location corresponding to bearings, output of gearbox. Xu Liang [15] et al. monitored vibration condition of wind turbine gearbox by acceleration sensors. And acceleration sensors are used in this paper too, thus vibration signals of each measuring point can be got varies with time. What’s more, time-domain vibration signal will be de-noised based on Haar-wavelet [16], and then frequency-domain signal can be obtained by performing Fast Fourier Transform (FFT) to handling signal.

There are totally 7 measuring points which are arranged on the cutting gearbox in this study, and they are described as figure 3. And acceleration vibration signals are tested with full load.

![Figure 3. Arrangement of measuring points.](image)

Time-domain vibration signals of each measuring point are analyzed, and the effective value, maximum value, and minimum value of each vibration signal are counted as table 3.

| Measuring point | Effective value (m/s\(^2\)) | Maximum value (m/s\(^2\)) | Minimum value (m/s\(^2\)) |
|-----------------|-----------------------------|---------------------------|---------------------------|
| 1               | 1.3                         | 5.6                       | -5.4                      |
| 2               | 1.1                         | 4.3                       | -4.2                      |
| 3               | 1.4                         | 5.5                       | -5.4                      |
| 4               | 0.87                        | 3.7                       | -3.7                      |
| 5               | 1.5                         | 6.6                       | -7.7                      |
| 6               | 2.1                         | 8.5                       | -8.6                      |
| 7               | 2.5                         | 11.1                      | -10.6                     |

It can be found that the effective value and the amplitude value of measuring point 7 are larger than other measuring points. That means, vibration energy of measuring point 7 is largest, and time-domain vibration signal of point 7 can be described as waveform in figure 4.

![Figure 4. Vibration waveform.](image)
Usually, vibration signals obtained by data collector often contain interference signals, so it is important to filter out noise signal before handling vibration signals. Noise reduction handling can be realized as decomposing and reconstructing signals, and time-domain signal shown in figure 5 is de-noised based on Haar-Wavelet. It can be seen from figure 5 that the signal is decomposed into 5 parts.

Appropriate threshold coefficients are chosen, and de-noised time-domain signal can be reconstructed from decomposed signal as shown in figure 5. Intercept a part of signal, it is shown as black part in figure 6.

![Figure 5. Decomposition of time domain signal.](image)

![Figure 6. Comparison of original signal and de-noised signal.](image)

It can be seen from figure 6 that slight periodic vibration is happened in the cutting gearbox. But there is no phenomenon of regular or irregular impact. Therefore, it can be judged basically that there
is no serious fault such as severe shaft bending and broken teeth. And excitation energy is not large enough to cause resonance of gear transmissions and gearbox housing.

FFT is conducted to de-noised signal, and the diagram of frequency spectrum can be shown as figure 7. It can be found from spectrogram that main carrier frequencies of vibration signal are meshing frequency and its multiple frequency of each gear transmission. Inherent frequencies of gearbox housing and each gear transmissions are not main carrier frequency. And this shows that there are no serious faults such as broken teeth and severe shaft bending.

Refining spectrum can be obtained by enlarging spectrogram of vibration signal near carrier frequencies, which is easy to observing side frequency. And it is helpful to research modulation phenomenon. Observing spectrogram near main carrier frequencies one by one, it is found that there is side frequency near the carrier frequency of 539 Hz, and its refining spectrum is shown in figure 8.

It can be seen from figure 8 that modulation frequency is 24Hz, and it is rotation frequency of first-stage axle and input axle of second-stage. Moreover, 539Hz is consistent with meshing frequency of second-stage gear transmission. This phenomenon shows that gear transmission of second-stage exist fault.

Therefore, the cutting gearbox is disassembled, and the gear pair of second-stage is checked, it is found that teeth surface of the gear pair is uniformly worn. And actual gear of second-stage transmission is shown as figure 9.

5. Conclusions
The following conclusions can be drawn:
(1) A novel method combining traditional formula and modal analysis to obtain mechanical parameters is proposed, and it provides a new idea for mining gearboxes with complex structure which are difficult to obtain mechanical parameters, especially inherent frequencies;

(2) Time-domain vibration signal is de-noised based on Haar-Wavelet, and Fast Fourier Transform is conducted to transform time-domain signal into frequency-domain signal. Thus vibration test can be researched from these two aspects, and failure of cutting gearbox can be diagnosed.

(3) Taking a cutting gearbox with complex structure as an example in this paper, vibration signal handling method proposed in this paper is performed when it is maintenance. And it is found that teeth surface of gear pair on second-stage transmission has uniform wear, which is consistent with actual situation and the effectiveness of the method is verified.

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