Research on Gearbox Fault Diagnosis Based on Vibration Signal Hilbert Demodulation

Dasheng Li, Hongling Ye and Yuqing Li
School of Mechanical and Vehicle Engineering, Bengbu University, Bengbu 233030, China
bbxyjdx@126.com

Abstract. Gears are often prone to typical faults such as broken teeth, pitting, tooth surface wear and shaft bending in harsh environments. These faults not only have different failure modes, but also have different vibration signal characteristics. Vibration signal analysis method is one of the most effective and adaptable methods in gearbox fault diagnosis analysis method. Based on the analysis of gearbox failure mechanism, this paper verifies the typical fault diagnosis of gearbox based on Hilbert demodulation analysis through specific experiments, the application of which provides an important reference for accurate gearbox fault diagnosis.

1. Introduction
The operating state of the gearbox plays a crucial role in the normal operation of the entire mechanical equipment. Condition detection and fault diagnosis of the gearbox can fundamentally change the status quo of after-sales maintenance and regular maintenance of the gearbox, and realize appropriate maintenance, thereby reducing the accident rate, reducing casualties and unnecessary economic losses, and creating more economic and social benefits[1-2]. At present, there are many methods for fault diagnosis of gearboxes, such as temperature measurement, oil sample analysis, vibration analysis, and acoustic measurement analysis. Because the vibration signal analysis method has better applicability, practicability and accuracy, etc. it has been widely used[3-5].

2. Analysis of gear vibration mechanism
The vibration system of the gearbox is a very complicated nonlinear system. It is difficult to establish a complete nonlinear vibration model when we conduct a research about gearbox fault diagnosis[6]. People usually simplify the vibration model by simplifying the gear transmission pair, thus deriving the gear meshing dynamics equation as figure 1.

\[ M \ddot{x} + C \dot{x} + K(t)x = K(t)E_1 + K(t)E_2(t) \quad (1) \]

\( M \)—equivalent quality, that is: \( M = (m_1m_2)/(m_1 + m_2) \)

\( X \)—Relative displacement of the gear along the line of action, that is: \( x = x_1 - x_2 \)

\( C \)—Gear meshing damping

\( E_1 \)—Average static elastic deformation of the gear after carrying

\( E_2 \)—Fault function

\( K(t) \)—Gear meshing stiffness
3. Edge frequency modulation phenomenon and Hilbert demodulation analysis principle

When the gear fails, a certain degree of modulation occurs, and a certain number of sidebands will be displayed in the spectrogram. When the faults are different, the form of the sidebands will be different[7]. These sidebands can reflect the gear fault information, but we need to effectively identify and analyze the gear vibration signal, and extract the type of gear fault represented by different types of sidebands. When the gearbox is faulty, the form of the sideband modulation is different in the spectrum due to the different forms and severities of the fault, but usually includes the following three forms: sideband modulation with carrier meshing frequency and its multiplication as the carrier. The side frequency modulation phenomenon in which the gear natural frequency and its frequency multiplication are carriers, and the side frequency modulation phenomenon in which the natural frequency of the gear box is the carrier. Therefore, an important step in fault analysis is to extract the modulation information[8]. Analyzing the intensity and frequency of the modulation information to determine the location and severity of the gearbox failure, whose analysis process is called demodulation. The resonance demodulation technology can be implemented in two ways, hardware resonance demodulation and software resonance demodulation. This paper adopts software demodulation method. The software demodulation is used to first collect the vibration signal of the fault bearing by the traditional method, and then takes the steps of bandpass filtering, envelope detection, low-pass filtering, spectrum analysis, etc. through the signal processing method, and finally diagnose the fault according to the envelope spectrum curve[9-11]. The basic process is shown in Figure 2.

\[ f_m = \frac{N}{60}Z \]  

(2)

\[ f_m = \text{gear meshing frequency} \]
\[ N = \text{the speed of the shaft where the gear is located} \]
\[ Z = \text{number of gear teeth} \]

When the gearbox has only one pair of gears engaged, the carrier signal of the gear meshing vibration is:

\[ x_m(t) = A \sin(2\pi f_m t + \phi) \]  

(3)

The modulation signal of the gear shaft rotation is:

\[ A(t) = 1 + m \cos(2\pi f_r t) \]  

(4)

\[ f_r = \text{Frequency shift of the axis of the gear} \]

Assume that the vibration signal of the gear is:

\[ x_m(t) = A_m [1 + m \cos(2\pi f_r t)] \sin(2\pi f_m t + \phi) \]  

(5)

The purpose of the Hilbert transform is to extract the amplitude modulated signal \( A_m [1 + m \cos(2\pi f_r t)] \).

4. Experiment

The experiment was carried out on the rotating machinery vibration analysis and fault diagnosis experimental platform. The platform consists of variable speed drive motor, gear train, bearing, shaft and governor. The platform can be used to perform a variety of fault simulations, including gear fault simulation, rolling bearing fault simulation, and shafting fault simulation. The experiment uses gears that have been treated with broken teeth and pitting, as figure 3 shown.
4.1 Gear broken tooth failure test

Gear breakage is a serious form of gearbox failure. During the meshing process of the gear, a large vibration shock will occur, and the vibration energy (effective value and kurtosis) will increase significantly. Regular shock can be seen in the time domain waveform after the autocorrelation denoising, the side frequency modulation phenomenon of the meshing frequency and its multiplication will be especially obvious in the frequency domain. Under normal circumstances, the broken tooth fault will arouse the natural frequency of the gear, that is, the natural frequency of the gear and its frequency-frequency modulation of frequency multiplication. The sidebands are generally large in number, wide in distribution, and large in amplitude. In the Hilbert demodulation spectrum, we can see the higher harmonics of the axis transposition of the broken gear, sometimes reaching 10 or more.

In the case of gear breakage failure example analysis, the smaller gear is a normal gear, which is mounted on the input shaft. The broken gear is a larger gear which is mounted on the output shaft. The acceleration sensor is mounted on the bearing housing of the gearbox output shaft. In the simulation experiment of the broken tooth fault, the actual working condition of the gear box is simulated, and the magnetic powder torsion device is used to simulate the load of about 1.5 Nm on the output shaft. The input shaft speed is 750RPM, and the gear output shaft is calculated to be 550 RPM according to the gear ratio calculation. The sampling frequency is 5120HZ during data acquisition, and the sampling point is 8192 points. According to the formula, the frequency of each gear in the gear meshing transmission and the meshing frequency of the meshing gear can be calculated separately. The specific analysis data is shown in Table 1.

| Gear name       | Number of gear teeth | Axis frequency shift | Meshing frequency |
|-----------------|----------------------|----------------------|-------------------|
| bigger gear     | 75                   | 9.17 Hz              | 687.5Hz           |
| Smaller gear    | 55                   | 12.5 Hz              | 687.5Hz           |

Figure 4 is the time domain waveform diagram of the measuring point of the broken tooth fault. It can be seen from the time domain waveform diagram that the time domain waveform of the broken tooth fault gear has a regular impact, and the impact energy increases, indicating that the gear has local damage. The impact time interval is approximately equal to 0.109S, which is the time taken for the output shaft to rotate one revolution. The impact gear has one impact per revolution.

Figure 5 is the frequency domain waveform diagram of the measuring point of the broken tooth fault. The meshing frequency of 671.63 Hz and its 2 times frequency 1345.16 Hz, 3 times frequency 2009.75 Hz and its side frequency modulation can be seen in the figure. The first-order natural frequency of the gear is 878.89 Hz and its side-frequency modulation are aroused by the broken tooth fault. To further confirm the analysis, the diagnosis is performed by Hilbert demodulation below. The Hilbert demodulation spectrum with narrow bandpass filtering at the center of the measuring gear with the gear meshing frequency of 671.63 Hz can be shown in figure 6. The frequency component close to the output shaft is 9.29 Hz, and its frequency doubling component is 18.75 Hz, 37.23 Hz, 46.39 Hz, 55.95 Hz, etc.,
12.88 Hz in the figure 5 is close to the input shaft frequency. However, there is also an unknown frequency component of 3.41 Hz, which is most likely due to the demodulation limitations of Hilbert. It is analyzed that the frequency should be the difference between the two axes. Figure 7 shows the Hilbert demodulation spectrum with narrow bandpass filtering at the center of the measuring point with the natural frequency of 878.89 Hz. The frequency component close to the output shaft is 9.39 Hz, and its frequency multiplication component is 18.33 Hz, 27.98 Hz, 37.13 Hz, 55.26 Hz, etc., 12.97 Hz in the figure is close to the input shaft frequency. However, there is also an unknown frequency component of 3.37 Hz, which is also likely due to the demodulation limitations of Hilbert. It should be analyzed that the frequency should be the difference between the two axes.

4.2 Gear pitting failure test
The slight pitting of the gears appears as a small number of sparsely distributed sidebands near the meshing frequency and its multiplier. However, severe pits will cause large pits, and a large periodic impact will occur during the gear meshing operation, and sometimes even modulate the natural frequency of the gear. The characteristics of severe pitting fault vibration signals are similar to those of gear teeth.

In the case of gear pitting failure case analysis, the same experimental equipment and parameter settings as the gear breaking fault test were used. The time domain waveform at the measuring point of the pitting fault gear will be shown in Figure 8. From the time domain waveform diagram, it can be seen that the pitting fault gear has a regular impact on the time domain waveform, the impact energy increases, and the impact time interval is approximately the same as the output shaft. The time spent in one week
is equal to 0.109S, that is, the impact gear has one impact per revolution, indicating that the gear has serious local damage.

Figure 9 shows the frequency domain waveform at the puncture fault gear measurement point. It can be seen that the meshing frequency of the faulty gear is 683.76 Hz and its side-frequency modulation, and the first-order natural frequency of the gear is 881.51 Hz and its side-frequency modulation. To further confirm the analysis, the diagnosis is performed by Hilbert demodulation below. Figure 10 shows the Hilbert demodulation spectrum with narrow bandpass filtering at the center of the measuring point with the gear meshing frequency of 683.76 Hz. The frequency component close to the output axis is 9.19 Hz, and its frequency multiplication component is 18.25 Hz, 27.31 Hz, 36.58 Hz, 45.84 Hz, 55.71 Hz, etc., the 12.53 Hz in the figure is close to the input shaft frequency. Figure 11 shows the Hilbert demodulation spectrum with narrow bandpass filtering at the center of the measuring point near the gear natural frequency of 881.51 Hz. The frequency component close to the output shaft is 9.33 Hz, and its frequency multiplication is 18.81 Hz, 27.95 Hz, 37.29 Hz, 47.12 Hz, and so on.

5. Conclusion
Due to the load, working environment and other factors, the gearbox has different fault modes, accompanied by corresponding vibration characteristics. Researching and exploring these vibration characteristics is a prerequisite for accurately realizing gearbox fault diagnosis. Through the detailed analysis of the time domain and frequency domain signals of the typical faults of the broken teeth, the vibration signal characteristics and diagnostic basis of these typical faults are verified, and the effectiveness of the Hilbert demodulation method is further illustrated. At the same time, it can be seen that the serious faults which appear in the gears, such as the severe pitting fault vibration signal
characteristics and the gear breaking teeth are similar. If strict distinguishing those two is needed, other methods will be adopted for analysis.

Acknowledgments

This work is supported by the Key Research Project of Natural Science in Universities in Anhui under Grant No.KJ2017A566, KJ2016A457 and Quality Engineering Project of Anhui Provincial Department of Education under Grant No.2017sxzx39.

References

[1] BonnardotF, El BadaouiM, RandallB, DanièreJandGuilletF2005Mech. Syst. Signal Pr.19 766
[2] HajnayebA, GhasemlooniaA, Khadem, EandMoradiH2011 Eepert Syst. Appl. 38 10205
[3] Konar P, Chattopadhyay P2015 Appl. Soft. Comput.30 341
[4] Lei Y, Lin J, Zuo MJ and He Z2014 Measurement48 292
[5] Singh S, Kumar N2017IEEE T Ind. Inf.13 1341
[6] Chen H, Lu Y, Tu L2013Shock Vib.20 247
[7] Goyal D, Pabla BS, Dhami SS2017Arch. Comput. MethodE.24 543
[8] Nam JS, Park YJ, Kim JK, Han JW, Nam YYand Lee GH 2014J. Mech. Sci. Technol.28 3033
[9] Chen XW, Feng ZP2016Mech. Syst. Signal Pr.80 429
[10] Gui Y, Han QKand Chu FL2016J. Mech. Sci. Technol.30 109
[11] Yu J, Huang WTand Zhao XZ, 2016 Proc. Inst. Mech. Eng. C-J. Mech. Eng. Sci. 230 303