Gear tooth breakage analysis based on multi-order modulated sideband RMS trending method

Jian'gang Chen1,2, Zhi Luo1,2,*, Ronggen Wu1,2 and Haiyang Cai1,2

1 Zhejiang Province Key Laboratory of Wind Power Technology, Hangzhou, Zhejiang, 310000, China
2 Zhejiang Windey Co., Ltd, Hangzhou, Zhejiang, 310000, China
*Corresponding author’s e-mail: luoz@chinawindey.net

Abstract. The fault characteristic signal energy for early gear tooth breakage is relatively weak and easily drowned by other signals, which is not conducive to the study of the fault development stage. A multi-order modulated sideband RMS (Root Mean Square) trend analysis method is proposed to analyse the development trend of the broken gear fault characteristics. By using this method to analyse gear breakage faults, the multi-order modulated sideband RMS trend analysis method can effectively determine the fault deterioration and fault stabilisation stages.

1. Introduction
The current use of modulated edge frequency characteristics to diagnose gearbox faults is mainly from the perspective of fault characterization to determine the type and severity of faults [1-4]. The edge frequency analysis method proposed by Chen Yonghui can locate the location and cause of the gear fault diagnosis [5]; Grabill P used the edge frequency parameter SLF to be able to identify the fault and normal state of the planetary wheel of the Black Hawk under the laboratory [6]; Kang Chuanzhang systematically analysed the causes of the modulated edge frequency signal formation from a theoretical perspective [7]. Few, however, have analysed the stages of development of gear breakage faults from the perspective of actual gearbox operating conditions. Combined with the important characterisation of modulated sidebands and RMS trend analysis of gear breakage faults, the "multi-order modulated sideband RMS trend method" is proposed to study the development trend of gear breakage faults, which has certain engineering significance for the fault diagnosis of gear breakage.

2. Gear fault diagnosis
The main types of gear failures are: pitting, shedding, cracking and broken teeth [8]. Broken teeth are late stage failures compared to other types of failures and need to be dealt with immediately. Therefore, the study of the development trend of gear tooth breakage faults is of great importance. After a broken tooth in one of the gear pairs, the time domain diagram exists for the rotational frequency of the broken gear and the meshing frequency shock of the gear pair. The above characteristics of the time domain and spectral diagrams are important fault characteristics of broken gears.

2.1. Full band, meshing frequency and modulation sideband combination RMS trend analysis
The object of the RMS trend analysis is the continuous vibration acceleration signals for the period before, during and after the failure of a pair of broken gear components. In chronological order, the trend of the RMS values of the vibration signals are plotted to analyse the vibration development pattern of
the faulty component. The actual complex gearbox condition, the vibration acceleration signal contains all levels of gear meshing frequency, each gear rotation frequency, bearing failure frequency and random noise, etc. The full band RMS trend analysis method cannot effectively display the RMS trend for non-maj or faults that are easily "flooded" [9]. For example, bearing faults or broken tooth shocks are easily "swamped" by gear meshing and engagement frequency faults, so full band RMS trend analysis is difficult to show the trend of broken teeth.

To address the limitations of the full band RMS trend analysis method, a combined multi-order meshing frequency and modulation sideband RMS trend analysis method is proposed. The method steps are simplified as follows.

1) Selection of vibration acceleration signals in a certain speed range.
2) Calculating the rotational frequency and gear mesh frequency of the faulty gear.
3) To obtain the combined signal of the multi-order gear mesh and its rotational frequency sidebands of the faulty gear pair by band-pass filtering the full frequency band signal.
4) Calculate the RMS value of the combined multi-order gear mesh and sideband signal and plot the timing of the RMS trend.

The full band RMS trend analysis method and the multi-order meshing frequency and modulation sideband combination RMS trend analysis method were used to analyse the gearbox vibration acceleration signal of the 2-stage shaft system pinion broken teeth. The 3-stage speed increase gearbox transmission schematic diagram is shown in Figure 1. The rotor Rotor rotates and drives the 1-stage planetary gear system PLS Sun Z3, which in turn drives the 1-stage shaft system to rotate the Z4 gear, the Z5 gear meshes with the Z4 gear and drives the 2-stage shaft system SRS1, the Z6 gear meshes with the Z7 gear and drives the 3-stage shaft system SRS2, and finally drives the generator Generator.

![Fig.1 Diagram of 3-stage incremental gearbox drive](image)

Information on key drive chain parameters and vibration acceleration data to be analysed for the 3-stage incremental gearbox are summarised in Table 1, with the broken tooth fault gear being the Z5 gear of the 2nd shaft train.

The acceleration data for the gearbox 3-stage shaft system in the speed range of 1650-1750 rpm for the period from October 1, 2020 to January 15, 2021 was selected for analysis by considering the following five factors.

1) the rated speed of the high-speed shaft of the gearbox is 1800 rpm.
2) the RMS value indicates, to a certain extent, the amplitude of the vibration at the location of the sensor measurement point.
3) the higher the speed the higher the vibration amplitude of the gearbox.
4) the actual speed of the gearbox is combined to ensure adequate analysis data.
5) The fault was found on 20 November 2020 and repaired on 8 December 2020.

| Item                          | Content                                |
|-------------------------------|----------------------------------------|
| Location of sensor measurement points | 3-stage shaft system output shaft radial |
| Date of data collection       | 2020.10.01-2021.01.15                  |
| Sampling frequency (Hz)       | 25600Hz                                |
| Individual data length (points) | 102400                                |
| Total amount of data (points) | 310*102400                             |
| R - 3-stage shaft system speed (rpm) | 1650-1750                           |
| Z7-Number of gear teeth       | 24                                     |
| Z6 - number of gear teeth     | 125                                    |
| Z5 - Number of teeth (broken gears) | 21                              |

The relevant engagement frequencies and frequency of rotation are calculated as shown below.

\[ f_{m1} \]: The 1st order meshing frequency (Hz) of the Z4 / Z5 gears is given in equation (1).

\[ f_{m1} = \left( \frac{Z7 \times R}{60} \right) \times \left( \frac{1}{Z5} \right) \]  

(1)

\[ f_{band} \]: Z5 gear rotational frequency sidebands (Hz), calculated as in equation (2).

\[ f_{band} = \left( \frac{Z7 \times R}{60} \right) \times \left( \frac{1}{Z6} \right) \]  

(2)

\[ f_{m2} \]: Z4 and Z5 gears 2nd order meshing frequency (Hz) is given in equation (3).

\[ f_{m2} = f_{m1} \times 2 \times f_{m1} \times 3 \]  

(3)

\[ f_{M1} \]: The 1st order meshing frequency (Hz) of the Z4 / Z5 gears is given in equation (1).

\[ f_{M1} = \frac{Z7 \times R}{60} \]  

(4)

Taking the 3rd stage shaft system speed R=1700 rpm, \( f_{m1}=114.20\) Hz, \( f_{m2}=228.40\) Hz, \( f_{m3}=342.60\) Hz, \( f_{band}=5.44\) and \( f_{M1}=680.00\) Hz.

As the broken tooth fault gear is the 2nd axis system Z5 gear, characterised in the spectrum as Z4 and Z5 gear vice multiple order meshing frequency and Z5 gear rotational frequency signal modulation phenomenon, all the RMS trend analysis of the first 3 order meshing frequency of the 2nd level axis system and Z5 gear rotational frequency sideband combined signal. the RMS trend is shown in Figure 2.

![Fig.2 RMS trend of full frequency band, meshing frequency and sideband combination](image-url)
Figure 2.a shows the RMS trend for the full band signal and Figure 2.b shows the RMS trend for the combination of the meshing frequency and modulation sidebands. Figure 2.a shows a slight overall increase in RMS values from 10/30 onwards, with an unclear stage of gear fault development; the bottom of RMS increases overall in the BC interval in Figure 2.b.

For the RMS trend in Figure 2, the 10/30 raw vibration acceleration signal from the BC section was analysed in Spectrum Figure 3, showing that the first 3 steps of the 3-stage shaft system (681Hz) signal is the dominant component in the 0-3000Hz band compared to the first 3 steps of the 2-stage shaft system (114Hz), "drowning out" the characteristic signal of the Z5 gear of the 2-stage shaft system [9]. The vibration generated by the Z5 gear breakage also contributes to the increase in amplitude of the drive components of the 3-stage shaft system [10], resulting in a slight overall increase in RMS in the BC region in Fig. 2.a, but does not effectively characterise the breakage failure trend. Figure 2.b shows the RMS trend of the combined signal of the first 3rd order engagement frequency and its Z5 rpm sideband for the 2-stage shaft system. After removing the influence of the 3-stage shaft system, the fault occurrence interval of the broken tooth can be found, but the deterioration trend of the fault is not obvious.

2.2. Multi-order modulation sideband RMS trend analysis
In response to the shortcomings of the combined RMS trend analysis method of meshing frequency and modulation sidebands, which can find the fault occurrence interval of broken teeth, but the deterioration trend of the fault is not obvious, the RMS trend analysis method of rotating frequency sidebands is proposed to analyse the trend of the fault. The method steps are simplified as follows.
1) Selection of vibration acceleration signals for a certain speed range.
2) Calculating the rotational frequency and gear mesh frequency of the broken gear.
3) To obtain the combined signal of the multi-stage gear mesh and its rotational frequency sidebands of the faulty gear pair by band-pass filtering the full frequency band signal.
4) Removing the 2-stage shaft system meshing frequency and its harmonic signal to obtain the multi-order stage shaft system faulty gear rotational frequency sideband signal.
5) Calculate the RMS value of the multi-stage 2-stage faulty gears and plot the trend.

The results of the RMS trend analysis of the first 3 steps of the 2-stage shaft system Z5 gear rotation frequency sidebands are shown in Figure 4. The RMS value gradually increased in the AB zone; the RMS value remained stable in the BC zone; the RMS value decreased linearly in the CD zone; the RMS value remained stable after point D and was basically the same in the zone before point A. It is basically consistent with the time point of fault discovery on November 20, 2020 and fault repair on December 8, 2020.
3. Conclusion
The multi-order modulated sideband RMS trend analysis method is more effective in identifying the deterioration and stabilisation phases of gear breakage faults than the combined multi-order full band and meshing frequency and rotational frequency sideband methods.

References
[1] He Jun. Research on vibration characteristics analysis and intelligent fault diagnosis method of gearbox [D]. Zhejiang University, 2018: 7-15
[2] Lei Yaguo, He Zhengjia, Lin Jing, Han Dong, Kong Detong. Research progress of fault diagnosis technology for planetary gearboxes[J]. Journal of Mechanical Engineering, 2011, 47(19): 59-67.
[3] Ding Kang. Practical techniques for fault diagnosis of gears and gearboxes [M]. Machinery Industry Press, 2005: 12-18
[4] Randall R B. Vibration-based Condition Monitoring: Industrial, Aerospace and Automotive Applications[M]. John Wiley & Sons, 2011: 167-169
[5] Chen YH, Jiang X, Li HH, Zhang XL. Gear fault diagnosis based on edge frequency analysis[J]. Mechanical Transmission, 2010, 34(06): 58-61.
[6] GRABILL P. Vibration monitoring of UH-60A main transmission planetary carrier fault[C]. 59th Annual Forum of American Helicopter Society. May 6-8, 2003. Phoenix, Arizona, USA. 2003: 1-11.
[7] Kang Chuanzhang, Chen Bingkui, Zhang Jing, Tan Rulong. Study on the side band of vibration signal of gear system and its application[J]. Mechanical Transmission, 2013, 37(04): 41-43+76.
[8] Liang X, Zuo M J, Feng Z. Dynamic modeling of gearbox faults: A review[J]. Mechanical Systems and Signal Processing, 2018, 98(jan.1): 852-876.
[9] Liu, Tao, Chen, Jin, Dong, Guangming. Research on rolling bearing fault diagnosis based on frequency band entropy[J]. Vibration and Shock, 2014, 33(01): 77-80.
[10] Li RF, Wang JJ. Gear system dynamics: vibration, shock, noise [M]. Science Press, 1997. 156-160