

# **Fault diagnosis of gear transmission system on LMD and Cyclostationary Demodulation**

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## **Abstract**

Gear transmission system is as an important part of the vehicle, and its work reliability directly affects the working performance of vehicle. A JZQ-250 gear transmission system is as the object, and the gear's and bearing's characteristic frequencies of gearbox are got by analyzing the test platform, structure parameters, operating principle, and the layout of measuring point. The vibration signals are collected and analyzed in normal status, tooth wear, and outer ring failure condition under the motor speed as 600r/min, the sampling frequency for 4000Hz. By using cyclostationary demodulation method, directly demodulate the vibration signals, and get their cyclic spectrum and cycle frequency axis projection, and analyze the frequency aliasing phenomena. By using the local mean decomposition, obtained time-frequency distribution can clearly and accurately reflect the distribution regularities of signal energy in space various scales. First LMD decomposition downs to the vibration signal as individual components' modulated signal, the calculation of energy of various components, and normalization processing, wherein the decomposed energy concentrated product functions proceeded the cyclostationary demodulation, obtained their cyclic spectrum, then the cyclic spectrum are combined and analyzed slices map in mesh frequency, they inhibit the influence of cross interference items directly use cyclostationary demodulation.

## **Keywords**

Gear transmission system, fault diagnosis, LMD, Cyclostationary Demodulation, vibration signal

## **1. Introduction**

In all types of machinery and equipment, gear transmission is the uppermost driving method, and the operational status of gear transmission system directly affects the performance of the mechanical equipment [1]. When the internal parts of gear transmission system such as gears, shafts and bearings break down, significant modulation phenomenon will produce [2]. JZQ-250 transmission gearbox system is as the study object, its structure parameters, operating principle, the layout of measuring point and characteristic frequency are studied. The modulated vibration signals are directly demodulated by using cyclostationary demodulation method [3] in normal status, and by fusing the local mean decomposition [4-6] with cyclostationary demodulation in tooth wear, and outer ring failure condition under the motor speed as 600r/min and the sampling frequency for 4000Hz.

In the cyclostationary demodulation and LMD, many scholars have done a lot of work. For example, Mr. Du studied the second-order cyclic statistical properties, confirmed the second-order cycle statistics for the mechanical fault signal demodulation process, more conducive to identification Fault characteristics [7]. Dr. Bi proved that the analysis of the gear modulation information can be accurately reflected when the spectral correlation density is used on the cyclical demodulation of the vibration signal under the weak gear [8]. Jonathan S. Smith proposed a new signal time-frequency processing method (Local Mean Decomposition (LMD)) in 2005. The signal is decomposed by LMD, which consists of a complex multi-component FM-AM signal into a series of linear combinations of Production Function (PF), where each PF function is multiplied by an envelope signal and a pure FM signal, so that the instantaneous amplitude of the original signal can be calculated by the envelope signal, and the instantaneous

frequency of the original signal can be calculated by the frequency modulation signal, and the original signal can be time-frequency analyzed[9].

## 2. Experimental Study

### 2.1 JZQ-250 experimental platform

The structure of JZQ-250 can be seen from Figure 1, the test platform is relatively simple, just three shafts, input shaft is connected through the coupling with the motor, and the power is transmitted by the intermediate shaft Z1, and the power is transmitted to the output shaft by Z3, the output shaft is connected to the magnetic brake load, the whole system is fixed to a rigid foundation.

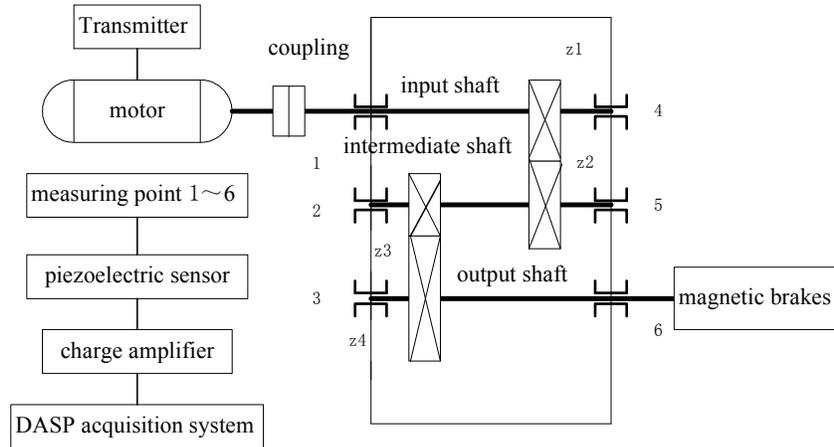


Figure 1. The test platform structure diagram of JZQ-250

Tables 1 and Table 2 are each parts parameters from JZQ-250.

Table 1. Structure parameters of bearings

| Bearing position   | Model | Bearing pitch diameter (mm) | Diameter of rolling element (mm) | Rolling element number | Contact angle |
|--------------------|-------|-----------------------------|----------------------------------|------------------------|---------------|
| Input shaft        | 6406  | 60                          | 19.05                            | 6                      | 0°            |
| Intermediate shaft | 6406  | 60                          | 19.05                            | 6                      | 0°            |
| Output shaft       | 6312  | 95                          | 22.225                           | 8                      | 0°            |

Table 2. The basic parameters of Gears

| Name of gear | Z1 | Z2 | Z3 | Z4 |
|--------------|----|----|----|----|
| Teeth number | 30 | 69 | 18 | 81 |

### 2.2 The gears and bearings characteristic frequency of JZQ-250

In order to get the bearings characteristic frequency of JZQ-250, inner circle characteristic frequency  $f_{ic}$ , outer circle characteristic frequency  $f_{oc}$ , rolling characteristic frequency  $f_{bc}$ , cage characteristic frequency  $f_c$  can be calculated according to formula 1-4. In formula, D for bearing diameter, d for rolling body diameter,  $\alpha$  for contact angle, Z for the number of rolling elements,  $f_r$  is the rotation frequency of shaft.

$$f_{ic} = 0.5Z \left(1 + \frac{d}{D} \cos \alpha\right) f_r \quad (1)$$

$$f_{oc} = 0.5Z \left(1 - \frac{d}{D} \cos \alpha\right) f_r \quad (2)$$

$$f_{bc} = 0.5 \frac{D}{d} [1 - (\frac{d}{D})^2 \cos^2 \alpha] f_r \quad (3)$$

$$f_c = 0.5 (1 - \frac{d}{D} \cos \alpha) f_r \quad (4)$$

According to the bearing characteristics frequency formula (1)-(4), the bearing characteristic frequency at a speed of 600r/min, as shown in Table 3:

Table 3. The bearing characteristic frequency of JZQ-250 gearbox (motor speed for 600r/min)

| Position           | Model | Inner circle (Hz) | Outer circle (Hz) | Rolling (Hz) | Cage (Hz) |
|--------------------|-------|-------------------|-------------------|--------------|-----------|
| Input shaft        | 6406  | 39.53             | 20.47             | 14.16        | 5.43      |
| Intermediate shaft | 6406  | 17.18             | 8.9               | 6.16         | 1.49      |
| Output shaft       | 6312  | 4.77              | 2.96              | 1.95         | 0.37      |

When speed is 1200r/min, the rotational frequency of drive shaft and mesh frequencies of each pair of gears can be calculated according to equation 5:

$$f_r = \frac{n}{60}, f_z = z f_r \quad (5)$$

Where,  $f_r$  is the rotation frequency of shaft,  $n$  is the rotational speed of drive shaft,  $z$  is number of gear,  $f_z$  is mesh frequency. According to Formula 5 and data in Table 2, the gear main frequency characteristics of JZQ-250 are shown in Table 4.

Table 4. Main features frequency of JZQ-250

| Motor speed 600r/min                       |       | Multiple frequency |        |        |       |
|--|-------|--------------------|--------|--------|-------|
|  |       | 2                  | 3      | 4      | 5     |
| Input shaft rotational frequency           | 10    | 20                 | 30     | 40     | 50    |
| Rotational frequency of intermediate shaft | 4.35  | 8.7                | 13.05  | 17.4   | 21.75 |
| Frequency of output shaft                  | 0.965 | 1.93               | 2.895  | 3.86   | 4.825 |
| Z1Z2 mesh frequency                        | 300   | 600                | 900    | 1200   | 1500  |
| Z3Z4 mesh frequency                        | 78.26 | 156.52             | 234.78 | 313.04 | 391.3 |

### 2.3 The measuring point selection of JZQ-250

The JZQ-250 gear transmission system is sealed structure, the vibration signal from faulty parts can not directly obtain, the vibration signals from the housing needs indirectly collect, and the obtained vibration signals can truly and accurately reflect the running state of the gear transmission system, it is the gear transmission system diagnosis premise. Rolling bearing is as example, when rolling bearing occurs in a fault, the generated vibration transmits the surrounding by the hemisphere waves, and transmits to the housing by the relevant parts. These shock vibrations contain high frequency components, the bearing failure is transmitted one time when it passes through the each relevant part, and it will lose about 80% of energy. In order to accurately measure, and collected signal needs be strong, the measuring points need arrange nearby load zones of the bearings, also should consider the structure and layout of the gear transmission system, as far as possible the measuring points directly arrange right above from the bearing block force point. Measuring points locations in experimental platform are as shown in Figure 1.

### 2.4 Project Settings

The gear is the largest failure probability parts of gear transmission system, which failure rate occupies 60% of the overall, and secondly, bearing failure also occupies 19% proportion, and 90% of bearing failures occurred in the inner circle and the outer circle, the other faults occur in the rolling element, and the cage rarely fails. In the paper, fault state analyzes based on three states set, they are the normal state, the gear fault state, and the bearing outer ring. Table 5 lists the fault type of experimental platform.

Table 5. The fault setting comparison from test platform

| Setting                | Type            | Location                          |
|------------------------|-----------------|-----------------------------------|
| Normal condition       | Normal          | —                                 |
| Gearbox fault settings | Broken tooth    | Broken tooth fault is set in Z2   |
| Bearing Fault Status   | outer race pits | 6406 bearing in measuring point 5 |

### 3. Working condition analysis

#### 3.1 The normal condition analysis of JZQ-250

Firstly, trouble-free bearings and gears are tested on the JZQ-250 experimental platform, the motor speed is set as 600r/min, the sampling frequency is 4000Hz, within 1s samples signal are selected and analyzed. Figure 2 is time-domain and power spectrum diagram of the gear transmission system under normal operating conditions. From the time domain figure, it can be seen the signal has a strong randomness, small rule changes, no rules to follow. From its power spectrum, the peaks in 30.27Hz and 49.8Hz can clearly distinguish, these frequencies match with 3, 5 multiple frequencies from the rotational frequency 10Hz, also there are the peaks in 79.1Hz, 159.2Hz, 297.9Hz and 595.7Hz, which are very consistent with mesh frequency of Z3Z4 (78.26 Hz) and its 2 multiple frequency, and mesh frequency of Z1Z2 (300Hz) and its 2 frequency multiplication, the modulation sidebands are not significant nearby the gear mesh frequency, they indicate that the gear transmission system operates normally.

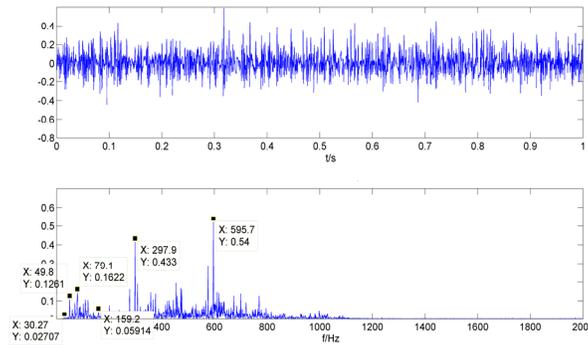
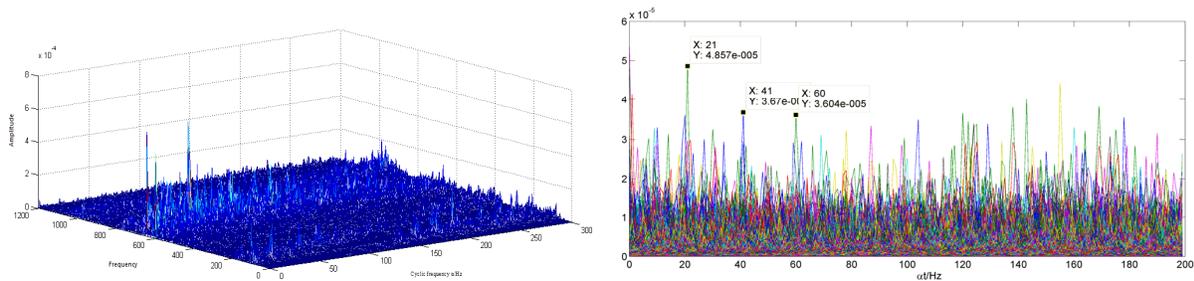


Figure 2. The time-domain and power spectrum diagram of JZQ-250 gear transmission system under normal state

Cycle spectrum and cycle frequency spectrum axis projection under normal state is as follow Figure 3.



(a) The cycle spectrum of normal signal

(b) The cyclic spectrum projection in cycle frequency axis

Figure 3. Cycle spectrum and cycle frequency spectrum axis projection under normal state

Figure 3 (a) is the cyclic spectrum of normal vibration signal, Fig.3 (b) shows the cyclic spectrum projects to the cycle frequency axis direction. From Fig.3 (b) can be seen, the fault frequency from any component does not appear the peak in the cycle frequency, only finds peak in 21Hz, 41Hz and 60Hz, they are corresponding to the input shaft rotational frequency of 10Hz and they are its 2,4,6 multiple frequencies, and they imply the gear transmission system works in normal state.

### 3.2 Gear fault condition

The work condition analysis of JZQ-250 gear transmission system in broken tooth.

In the experiment, Z2 sets a gear broken tooth fault, the motor speed is as 600r/min, the sampling frequency is 4000Hz, selected within 1s samples signal are analyzed. Figure 4 is the time-domain and power spectrum diagram under the conditions.

Broken tooth fault is serious in JZQ-250 experimental platform, so there is visible shock component in the time domain; there are clearly significant peaks at 78.13Hz, 297.9Hz, 605.5Hz and 903.3Hz in its spectrum, and 78.13Hz are very close with 78.26Hz, which is the mesh frequency of Z3Z4. 297.9Hz, 605.5Hz and 903.3Hz are very close with the mesh frequency of Z1Z2 (300Hz) and its twice and triple frequency. The modulation sidebands are confusing in both sides, it is difficult to obtain modulation information, and it can not determine the gear broken tooth. In order to correctly extract fault features, accurately identify, the spline-based LMD method is used to finish the vibration signal decomposition, the results shown in Figure 5.

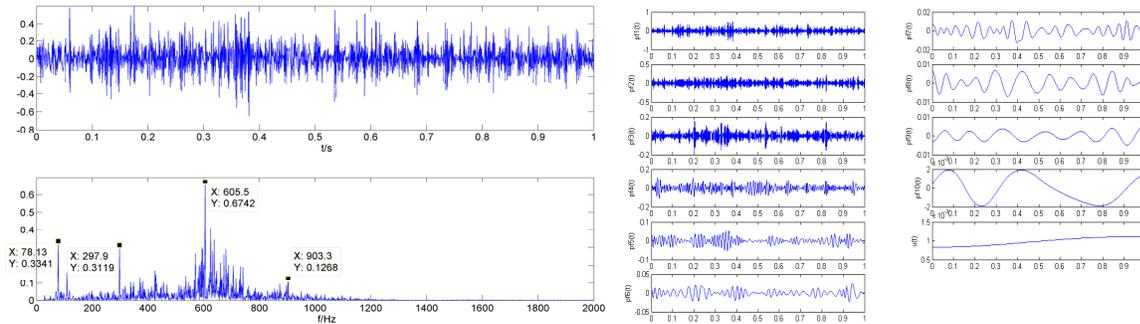


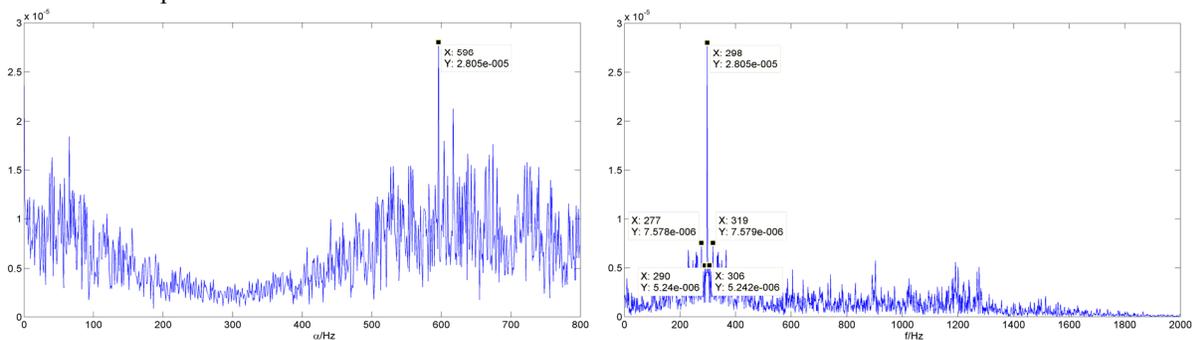
Figure 4. The time-domain and PSD under broken tooth Figure 5. LMD exploded view in broken tooth

It can be shown from Figure 5, the vibration signals are decomposed into a total of 10 product functions components and a residual component, energy values of the various components except the residual component are calculated, and normalized, the results shown in Table 6.

Table 6. The normalized energy of LMD component under broken tooth

|           |       |       |                      |                      |                      |
|-----------|-------|-------|----------------------|----------------------|----------------------|
| Component | PF1   | PF2   | PF3                  | PF4                  | PF5                  |
| Energy    | 0.61  | 0.21  | 0.08                 | 0.06                 | 0.01                 |
| Component | PF6   | PF7   | PF8                  | PF9                  | PF10                 |
| Energy    | 0.004 | 0.001 | $6.9 \times 10^{-4}$ | $3.2 \times 10^{-4}$ | $0.6 \times 10^{-5}$ |

As can be seen from Table 6, from the beginning of PF5, each PF energy is less one order of magnitude than the previous, so energy is concentrated on the first four components of them, select the first four components to conduct cyclostationary demodulation, obtained cyclic spectrum and their combined cyclic spectrum, Fig.6 (a) and Fig.6(b) are the slice maps at  $f = 297.9\text{Hz}$  and  $f = 595.8\text{Hz}$ .



(a) The slice map in  $f=297.9\text{Hz}$

(b) The slice map in  $f = 595.8\text{Hz}$

Figure 6. The slice map of the broken tooth cycle spectrum

It can be shown from Fig.6(a), there is clearly significant peaks at cycle frequency 596Hz, it is very close with the twice mesh frequency of Z1Z2. Its sides modulation sidebands confusing, it is difficult to obtain modulation information. From Fig.6(b), by observing  $f=595.8\text{Hz}$  slice map, a peak obviously appears at  $f=298\text{Hz}$  and at both sides, 277Hz, 290Hz, 319Hz and 306Hz obviously appear spectrum line, in these frequencies, modulation sidebands are formed around the mesh frequency at 277 Hz and 319 Hz according to approximately five times the rotational frequency (21.75Hz), modulation sidebands are formed around the mesh frequency at 290Hz and 306Hz according to approximately twice rotational frequency (8.7Hz), they show spectrum correlation by using second-order cyclic statistics can easily identify the gear broken tooth fault.

To verify the method can inhibit the cross-term interference, directly get the cyclic spectrum of the original signal and its slice map at  $f=297.9\text{Hz}$ , as shown in Fig.7. There are many frequency peaks in the cycle spectrum, which contain a number of cross-interference terms, their slice maps clearly appear mixed phenomenon in the cycle frequency 202Hz, 399Hz, 897Hz and 917Hz etc., and they cause the interference to diagnosis result, by comparing, Fig. 6(b) effectively suppressed the cross-interference terms.

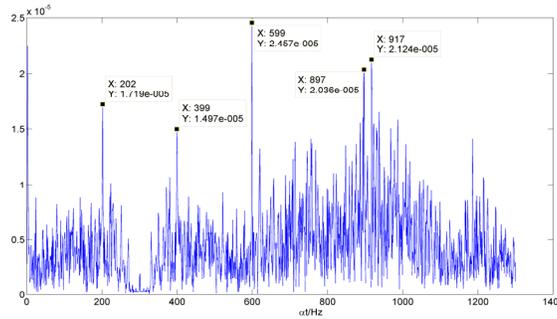


Figure 7. The slice map on pre-improved cycle spectrum

### 3.3 The outer circle fault condition of JZQ-250 gear transmission system

The 6406 bearing outer ring fault data in V measuring point, the motor speed is 600r/min, the sampling frequency is 4000Hz, within 1s signal samples are selected and analyzed. The time domain and power spectrum of the condition is shown in Figure 8.

It can be seen from Fig.8, there are the visible shock components in the time domain; in power spectrum, there are obvious amplitudes at 79.1Hz, 297.9Hz and 595Hz, these frequencies respectively corresponding to mesh frequency (78.36Hz) of Z3Z4, the mesh frequency of Z1Z2 (300Hz) and its 2 multiple frequency. Both sides from 297.9Hz and 595.7Hz can see the edge frequencies, the frequency interval has very great difference with the bearing fault characteristic frequency (8.9Hz) and its multiples, therefore, it can not determine what kind of failure has occurred. The feature extraction is finished by a new algorithm. That is, first LMD decomposition of the original signal, Figure 9 is LMD decomposed components of an original signal.

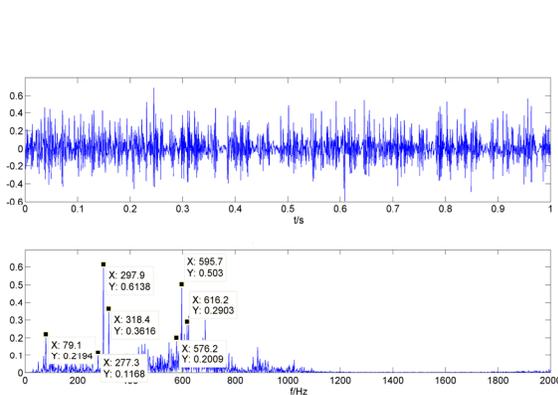


Figure 8. Time domain and PSD of outer-ring fault

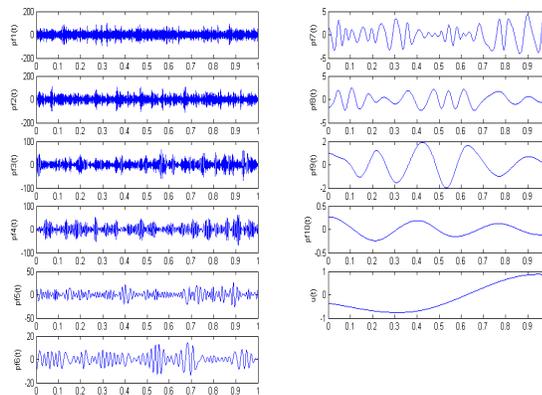


Figure 9. LMD exploded view of the outer ring fault signal

From Fig.9 can be seen, the vibration signals are decomposed into 10 products function components and a residual component, energy values for each component are calculated except the residual component, and normalized, the results shown in Table 7.

Table 7. Normalized energy on LMD component under the outer ring fault

|           |       |       |                      |                      |                      |
|-----------|-------|-------|----------------------|----------------------|----------------------|
| Component | PF1   | PF2   | PF3                  | PF4                  | PF5                  |
| Energy    | 0.5   | 0.27  | 0.1                  | 0.07                 | 0.03                 |
| Component | PF6   | PF7   | PF8                  | PF9                  | PF10                 |
| Energy    | 0.003 | 0.001 | $5.8 \times 10^{-4}$ | $4.6 \times 10^{-4}$ | $1.5 \times 10^{-4}$ |

As can be seen from Table 7, from the start of PF5, energy of each PF is less one order of magnitude than the previous, so the energy is concentrated in the first four components, the first four cycles spectral components are got and composed, and then the slice map at  $f=297.9\text{Hz}$  and  $f=595.8\text{Hz}$  are extracted as shown in Fig.10.

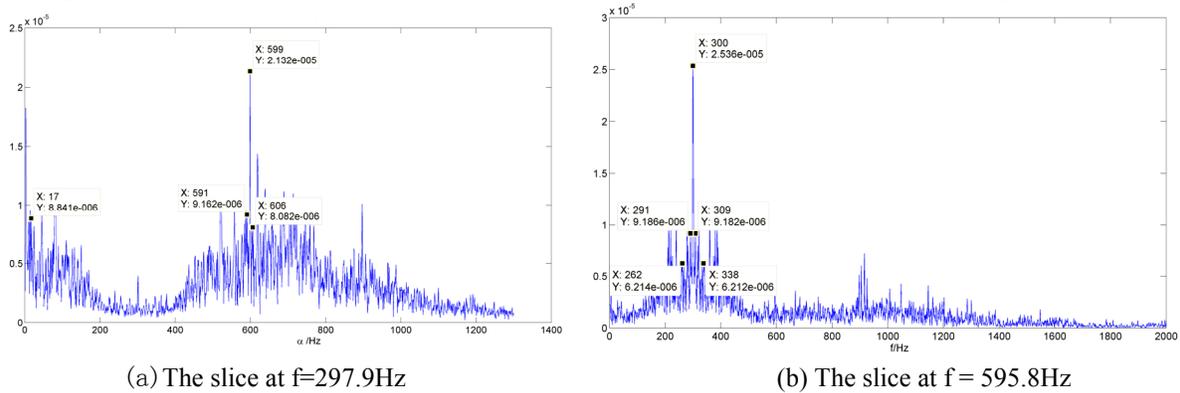


Figure 10. Slices spectrum of cyclic autocorrelation function

From Fig.10(a) can be seen the absolute peak appears at the cyclic frequency  $f=599\text{Hz}$ , it is close to the 2 multiple mesh frequency of Z1Z2, the modulation information does not easily observe; the significant amplitude at  $f=300\text{Hz}$  can be found when slice map at  $f = 595.8\text{Hz}$  is observed, and from Fig.10(b) around  $300\text{Hz}$  exists in the side frequency, which the frequency is  $291\text{Hz}$ ,  $309\text{Hz}$ ,  $262\text{Hz}$  and  $338\text{Hz}$ , wherein  $291\text{Hz}$  and  $309\text{Hz}$  are side frequencies which is approximately bearing fault frequency ( $8.9\text{Hz}$ ) as the intervals, and  $262\text{Hz}$  and  $338\text{Hz}$  are side frequencies which is approximately fourth fault frequency ( $35.6\text{Hz}$ ) as the intervals, they meet the fault phenomenon when a bearing outer ring occurs fault, they indicate that the method can effectively extract the fault characteristic at the bearing outer ring.

Figure 11 shows the cyclostationary demodulation of original signal and its slice map at  $f=297.9\text{Hz}$ , the frequency components in the slice map is relatively noisy, while the cyclic frequency equal to  $202\text{Hz}$ ,  $399\text{Hz}$ ,  $897\text{Hz}$  and  $917\text{Hz}$ , etc. appear at the mixing frequency phenomenon, they cause the disturbance to diagnosis result, Fig.10 (a) effectively suppressed cross-interference terms by comparing with Fig.11.

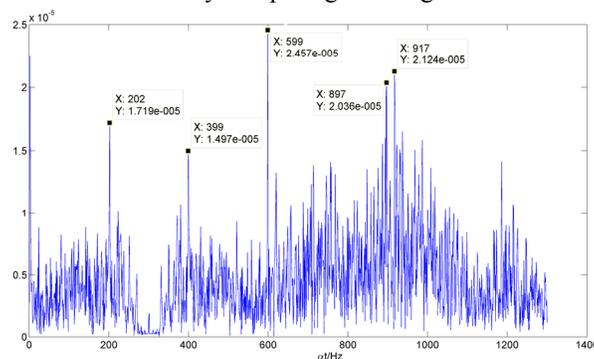


Figure 11. The slice map of pre-improved cyclic spectrum

#### **4. Conclusion**

Based on describing the basic components on JZQ-250 structural parameters, calculating the characteristic frequency of gear transmission system, analyzing the measuring points arrangement, setting working state and studying data collection methods; analyzing JZQ-250 gear transmission system under normal state, gear fault status and bearing fault condition based on the LMD cyclostationarity demodulation method. Aiming at the shortcomings of the second-order cyclostationarity statistics, it is easy to produce the cross-interference term when it demodulates the multi-component modulation signal. LMD decomposition method is used to decompose the signal into a single component, smooth demodulation, extraction characteristics. By the use of second order cyclic statistics and spectral correlation method can effectively extract the corresponding fault characteristics, and effectively suppress the influence of cross-interference terms in actual use, and they have the positive significance to diagnostic result.

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#### **Biography**

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Her research areas mainly focus on control technology, diagnosis of machinery-electronic system, and reliability etc. Since 2002, Dr Yao had directed 30 research programs, participated 25 programs, awarded 1 item for Ministry of Education nominated national scientific and technological progress secondary Award, and 5 items for Shanxi Province Science and Technology Improvement secondary Awards.