

# Study on the Influence of Rotation Speed on Face-Gear Meshing Vibration

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**Abstract-** Gear vibration signal contains all the information of gear meshing process; it could make a full, true and rapid response to the operating status of gear. By testing the vibration of different speeds of face-gear and analyzing the vibration signal from the extracted spectrum of harmonic amplitude, it was found that as the spindle rotation speed increases, the harmonic amplitude in each direction of the face-gear and spur gear was reduced. However, for the bevel gear meshing vibration testing, the adjusting vibration amplitudes in all directions were increasing. Therefore, the driven of face-gear is more suitable than the bevel gear for high speed transmission applications.

**Keywords:** Face-Gear; Meshing Performance; Spectrum Analysis; Harmonic Amplitude

## I. INTRODUCTION

According to the needs of the aviation industry development, the aviation gear is developed to the direction of high-speed, heavy load and light mass. Face-gear driven has the advantages of large degree of coincidence, insensitive to misalignment and without axial force. Especially, the stream - transmission of the unique nature of convergence makes it have unique superiority in the application of armed helicopter<sup>[1-2]</sup>.

Domestic and foreign scholars have researched the face-gear<sup>[1-7]</sup>. The meshing characteristics of gear transmission system will directly affect the stability and reliability of the driven system. Jin and Zhu studied the orthogonal plane of the nonlinear vibration characteristics of the gear transmission system<sup>[8]</sup>; Pang et al. simulated and analyzed the main gear box of the vehicle nonlinear vibration characteristics<sup>[9]</sup>, and studied on the main drive gear reducer vibration characteristics. Vibration and noise of gear meshing is an important indicator of meshing performance. Many scholars use the vibration and noise of gear meshing to diagnose faults. However, study of rotation speed affecting the gear mesh is rarely reported<sup>[10-16]</sup>. This article will research the influence of rotation speed on face-gear performance by using experimental methods and provide the basis for the design of face-gear transmission.

## II. CHARACTERISTIC ANALYSIS OF VIBRATION SIGNAL

Gear vibration signal contains the information in the process of meshing. It could fully, truly and rapidly reflect the operating status of gear. Therefore, the analysis of vibration signals plays an important role in gear meshing performance evaluation<sup>[9]</sup>. The analysis of gear vibration signal includes time domain, frequency domain and amplitude range. Frequency domain analysis is FFT transforming to the signal and getting the spectrum; the spectrum highlights the signal variation at each frequency. The characteristics of gear meshing could be analyzed by spectral characteristics.

Gear vibration signal is a stationary random signal, ideally, when the drive gear meshing,  $A_m$  expresses the harmonic amplitude,  $\varphi_m$  is the harmonic phase,  $f$  is the gear meshing frequency, then the vibration signal expressed mainly as frequency and its harmonic frequency components is<sup>[10]</sup>:

$$x(t) = \sum_{k=1}^N A_m \cos(2\pi f t + \varphi_m), \quad (1)$$

In which

$$f = \frac{mnZ}{60}, \quad (2)$$

where  $k$  is a natural number, is the maximum number of gear meshing frequency harmonics,  $z$  is the gear teeth, and  $n$  is the gear shaft rotation speed (rpm).

The changes in gear vibration signal amplitude and frequency (phase) are influenced by the fluctuation factors of gear load, stiffness and rotation speed, etc. It will produce the phenomenon of amplitude and frequency modulation. Therefore, considering the fluctuation factors, such as rotation speed, the gear vibration signal can be expressed as:

$$x(t) = \sum_{k=1}^N A_m [1 + a_m(t)] \cos[2\pi ft + \varphi_m + b_m(t)], \quad (3)$$

where  $a_m(t)$  is the amplitude modulation function, and  $b_m(t)$  is the phase modulation function.

Power spectrum is the energy of the vibration signal of a frequency and it is important information to study the gear vibration signals. The average power of vibration signal at time T is:

$$P_x(f) = \frac{1}{\Delta f} \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x^2(t, f, \Delta f) dt \quad (4)$$

The self-correlation functions between  $L_x(\tau)$  and  $P_x(f)$  is:

$$\begin{cases} P_x(f) = \int_{-\infty}^{\infty} L_x(\tau) e^{-j2\pi f \cdot \tau} d\tau \\ L_x(\tau) = \int_{-\infty}^{\infty} P_x(f) e^{j2\pi f \cdot \tau} df \end{cases} \quad (5)$$

$P_x(f)$  reflects the structure of frequency domain of the signal. The relationship between the power spectrum and amplitude spectrum  $X(f)$  can be derived by Barcelona Navarre Theorems:

$$P_x(f) = \frac{1}{T} \lim_{T \rightarrow \infty} |X(f)|^2 \quad (6)$$

The power spectrum estimation equation is:

$$\hat{P}_x(f) = \frac{1}{T} |X(f)|^2 \quad (7)$$

### III. TEST-BED FOR FACE-GEAR MESHING PERFORMANCE TEST

The vibration generated in the process of face-gear meshing will pass to the test machine. The system adopts three-axis acceleration sensor, detects spindle axial and radial vibration box, and converts the analog signals into digital signals through the collection card. It uses LABVIEW to collect vibration signals and make conditioning to corresponding signals. Meantime, it uses LABVIEW and MATLAB data interface and calls on the dealing programmer of the COM component based on Hilbert - Huang transform (Hilbert-Huang Transform, HHT) to display and store the processed data and charts.

#### A. Hardware of test-bed for face-gear performance test

The test-bed for face gear mesh performance test consists of the following hardware:

Rolling test machine-- YD9550 gear rolling test machine shown in Fig. 1(a); Acceleration sensor - three-axis acceleration sensor installed on the two gears seats for detecting surface of the gear meshing vibration signal; IEPE tri-axial accelerometer (J13510) from Shanghai North Chi; Noise sensor - Chongqing Thai measured TZ-2KA type; UA307Si type A / D acquisition card from Beijing mining companies.

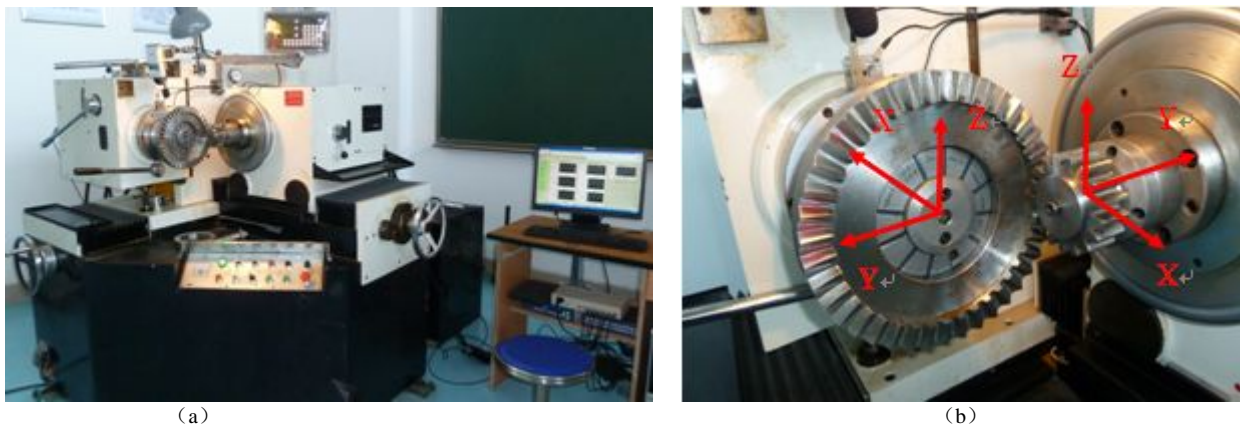


Fig. 1 Face-gear mesh vibration testing experiment

*B. Software of test-bed for face-gear performance test*

The system is a development platform with Lab view, using HHT transform as a signal processing method, collecting face gear meshing vibration and noise signals and analyzing them to determine the performance of face-gear meshing.

The testing software is modular in design programming ideas, including the master control, parameter management, data collection, data analysis and processing, data management and analysis results are displayed in six modules, as shown in Fig. 2. Main control module's functions are complete interface management, system initialization, testing and process control communication between modules. Parameters of the function management module are the system login password, sensor calibration parameters, the threshold criteria, working conditions and other parameters. Data acquisition module's functions are to achieve Lab view and capture card communication, and to achieve the noise and bearing vibration signal at the analog acquisition. Data analysis and processing module's function is to process noise and vibration signals in time domain and spectral analysis. analysis results display is face gear mesh performance evaluation functions; Data management module to complete the original data storage, data chart and time-domain spectrum of the complex is, database management and printing.

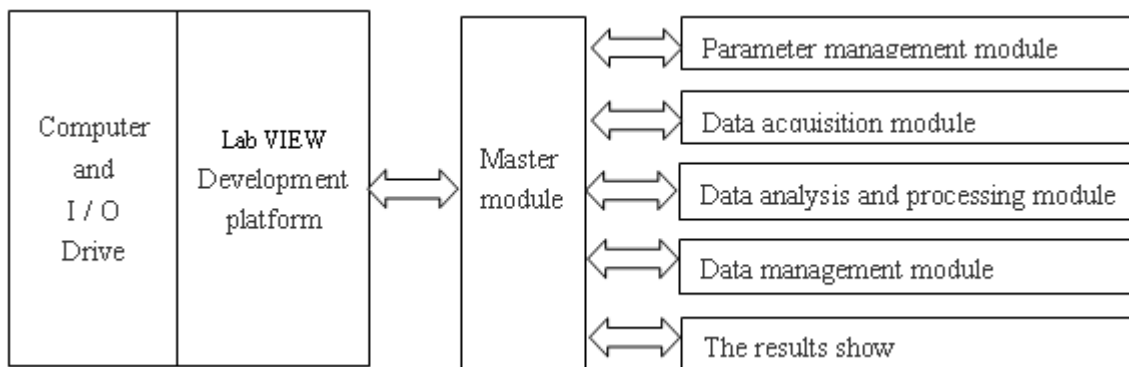


Fig. 2 Gear meshing function of the system performance test

IV. FACE-GEAR VIBRATION TESTING EXPERIMENT AT DIFFERENT ROTATION SPEEDS

TABLE 1 EXPERIMENTAL GEAR PARAMETERS IN FACE-GEAR MESHING PROCESS

Gear type	Gear module	Pressure angle	Cylindrical gear teeth	Face of gear teeth
Spur	5mm	20°	18	40

Spectral analysis as an important diagnostic method in the field sensors installed on the device, equipment vibration through basic information gathering, extraction equipment, the basic operation and fault conditions, development, and changing information, and then deal with the analysis of a fault diagnosis method.

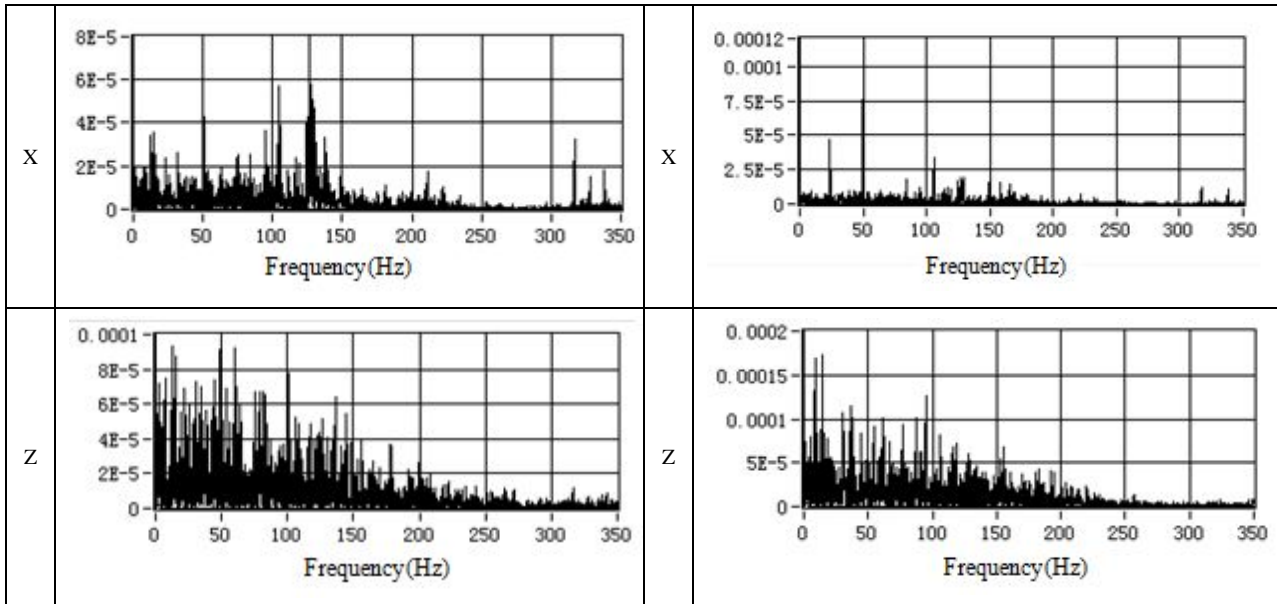
Face-gear coordinate system of the rolling test machine is shown in Fig. 1(b), where X is the face gear axis, Y axis is cylindrical gear, Z is the vertical radial direction. The face-gear installation distance is 100 mm, the installation distance of the cylindrical gears is 230.10 mm, offset distance is 37.295 mm, and face gear load is 20 N•m. According to surface meshing gear principle of orthogonal straight tooth gear, the spur gear has not axial force or radial force of face gear. Therefore, the test did not consider the Y-axis direction of the vibration signal.

The reagent coated with the opposite gear was installed on the test machine, as shown in Fig. 1. After adjusting the machine to normal mating and starting the machine, the input shaft speeds were 800,1000,1200 and 1400 rpm, and the input speed for each run by short-term dealt with testing machine spindle vibration signal.

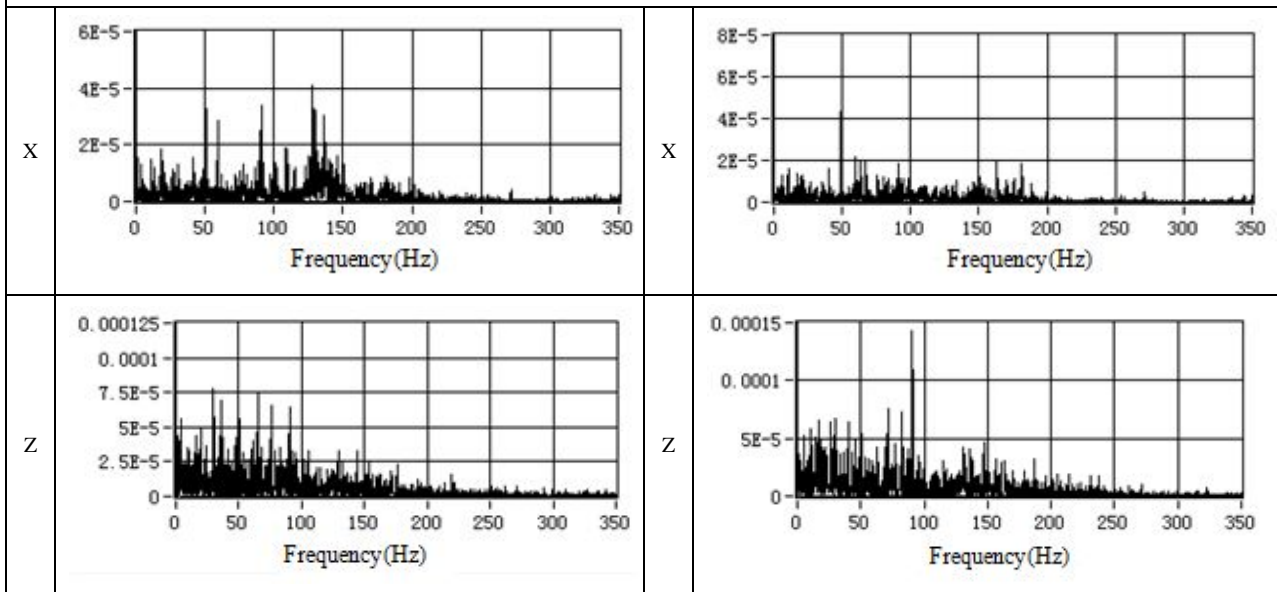
The following experiments measured different speed spur gear meshing with the gear surface vibration spectrum.

TABLE 2 VIBRATION SPECTRUM GRAPHICS IN MESHING PROCESS OF CYLINDRICAL GEARS AND FACE-GEARS AT DIFFERENT SPEEDS

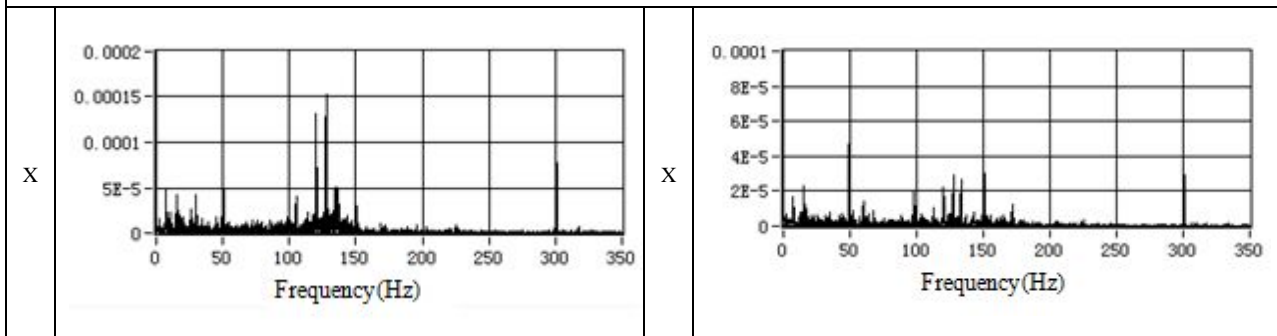
vibration spectrum in Face-gear mesh	vibration spectrum in Spur gear meshing
Cylindrical gear speed: 1400; Face-gear switch frequency: 10.5; Cylindrical gears switch frequency: 23.3333; Tooth frequency: 420; Detected fundamental frequency: 507.518.	

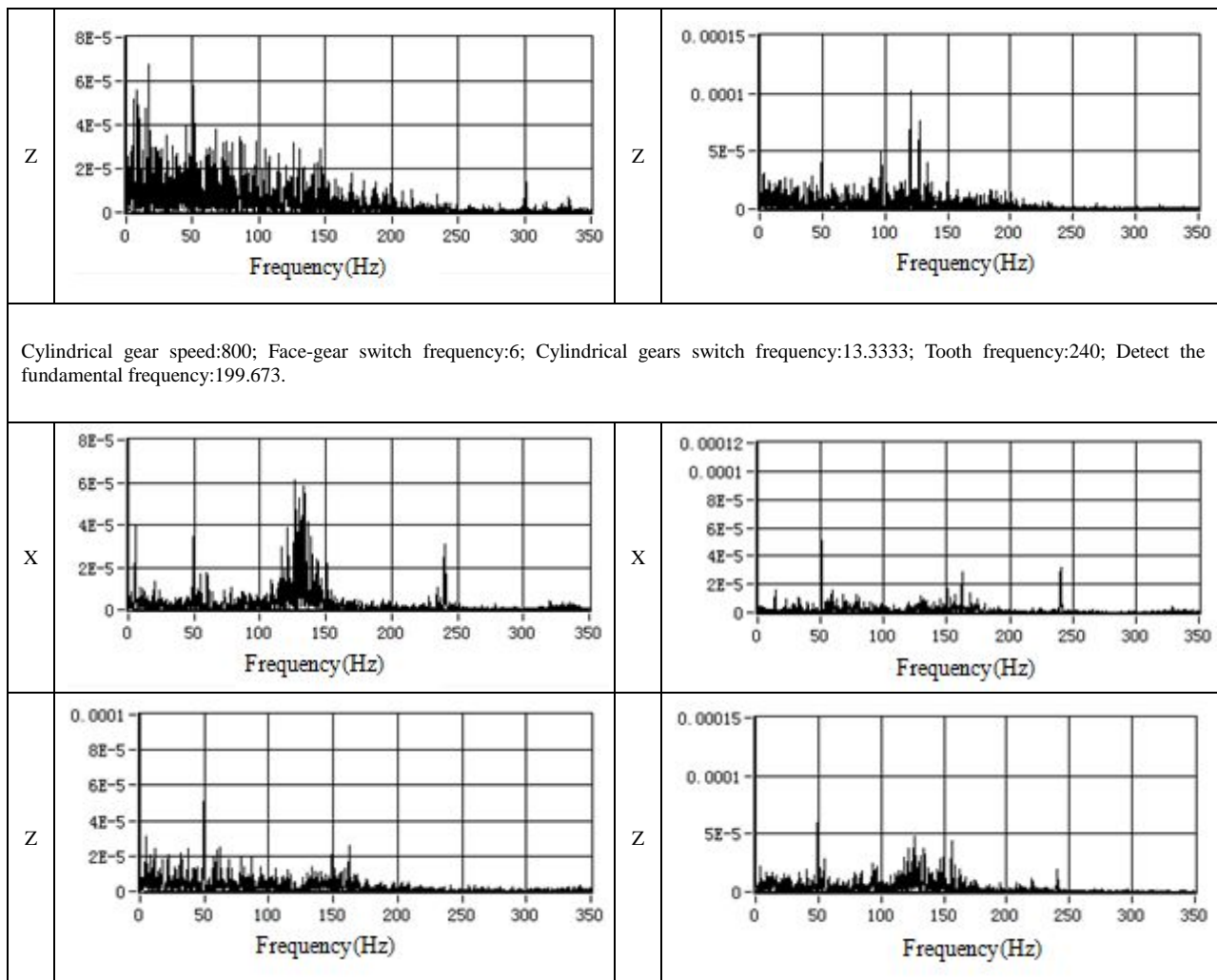


Cylindrical gear speed:1200; Face-gear switch frequency:9; Cylindrical gears switch frequency:20; Tooth frequency:360; Detect the fundamental frequency:399.693.



Cylindrical gear speed:1000; Face-gear switch frequency:7.5; Cylindrical gears switch frequency:16.6667; Tooth frequency: 300; Detect the fundamental frequency:340.244.





V. THE ANALYSIS RESULT OF FACE-GEAR VIBRATION SIGNALS AT DIFFERENT ROTATION SPEEDS

The vibration signal of gear meshing includes the fundamental frequency, high harmonic gear to gear meshing fundamental frequency and its higher harmonics is the carrier frequency to frequency as the gear shaft of the gear mesh frequency modulation frequency modulation sideband phenomenon arising from such. Among them, the 1<sup>st</sup> to 2<sup>nd</sup> harmonic generations are related to the tooth contacting area of the relative length and width, and the 3rd sub-harmonic generation is mainly related to the tooth surface roughness or interference related. Table 2 for the spectrum analysis, have come forward gears and cylindrical gears tone amplitude of 1 to 3 times the value of harmonics, as shown in Table 3.

TABLE 3 COMPARISON OF SPECTRUM ANALYSIS RESULTS IN MESHING VIBRATION PROCESS OF FACE GEARS AT DIFFERENT SPEEDS

Cylindrical gear Speed	Spectrum analysis							
	Tone amplitude of face -gear				Tone amplitude of cylinder gear			
	Coordinate	1 harmonic	2 harmonic	3 harmonic	Coordinate	1 harmonic	2 harmonic	3 harmonic
1400	X	0.000002	0.000000	0.000000	X	0.000001	0.000000	0.000000
	Z	0.000003	0.000002	0.000027	Z	0.000003	0.000000	0.000001
1200	X	0.000001	0.000000	0.000000	X	0.000001	0.000000	0.000000
	Z	0.000003	0.000000	0.000000	Z	0.000003	0.000000	0.000000
1000	X	0.000002	0.000001	0.000000	X	0.000000	0.000000	0.000000
	Z	0.000008	0.000002	0.000002	Z	0.000002	0.000000	0.000000
800	X	0.000004	0.000002	0.000000	X	0.000003	0.000001	0.000000
	Z	0.000010	0.000008	0.000000	Z	0.000004	0.000001	0.000000

Harmonic amplitude reflects the performance of meshing gears face gears from Table 3, extracted spectrum before comparing the value of the third harmonic, as the first harmonic is obvious, therefore, mainly a harmonic analysis, the results shown in Figure 3.

The experimental testing machine, X-axis direction of the face gear and spur gear is axial, Z axial direction, compared with face gear and spur gear of the radial, therefore, X-axis Z-axis direction than the rigidity of the great. As can be seen from

Figure 3, face gear meshing process, the direction of a face gear Z harmonic tone than the X direction of the large amplitude, this result is consistent with the theory.

As the spindle rotation speed increases, the surface of the gear meshing vibration will be reduced. And the vibration component in the Z direction decreased quickly, but the rotation speed is over 1200 rpm after the X direction of vibration of the gear face increased weight, Z direction of the vibration components unchanged.

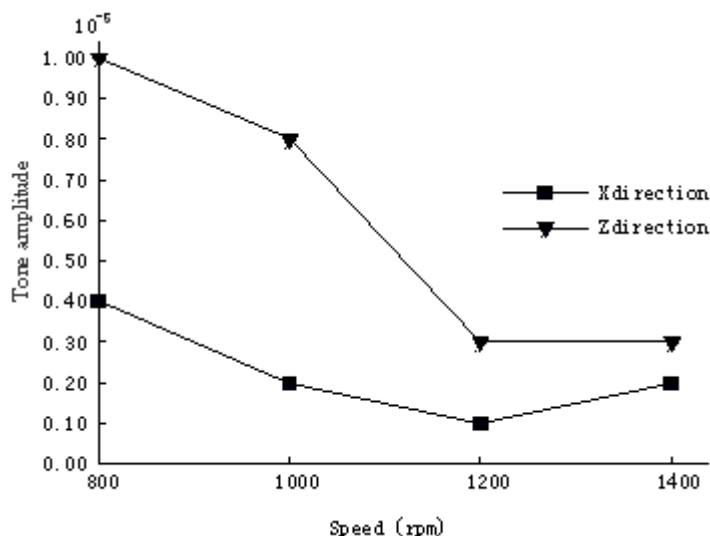


Figure 3 Different speeds of the surface when a harmonic gear-mesh amplitude adjusts

VI. THE INFLUENCE OF SPIRAL BEVEL GEAR ON THE MESHING PERFORMANCE AT DIFFERENT SPEEDS

Figure 4 shows the bevel gear test diagram. A 21-teeth pinion and a 47-teeth large gear were used. The installation distance of the large gear is 59 mm and that of the pinion is 100 mm, offset distance is 30 mm, and the load on large wheel is about 20 N•m, bevel gear rotation speed in different circumstances test, the results shown in Figure 5.



Figure 4 Performance testing of spiral bevel gear mesh experiment

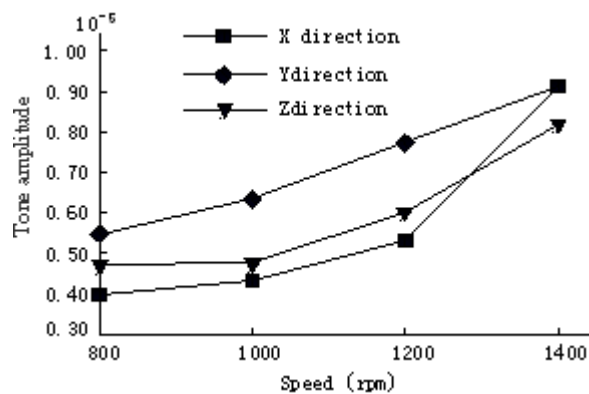


Figure 5 Different speed of the spiral bevel gear mesh adjustment when a harmonic amplitude

In the bevel gear meshing process, the meshing vibration increases gradually with the increase of the spindle rotation speed, and the vibration component of big wheel in the Y direction reaches the biggest. If the rotation speed is lower than 1000 rpm, big wheel in the respective radial vibration is greater than the axial vibration; when the speed exceeds 1000 rpm, the growing vibration component of big wheel in X direction would be the fastest.

VII. CONCLUSIONS

By testing the vibration of face gear and bevel gear at different rotation speeds and analyzing the spectrum obtained, the following conclusions were made in this study:

As the rotation speed increases, analysis of the meshing vibration spectrum shows that the face-gear and spur gear of the transfer amplitude were reduced, whereas the bevel gear meshing vibration amplitude of the tone was increased. Therefore, the face-gear transmission is more suitable for high-speed transmission compared with bevel gear transmission.

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