Fault diagnosis of mechanical spindle drive chain based on
time-frequency domain characteristics

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Abstract: As a key component of CNC (computer numerical control) machines, spindle’s performance directly affects the performance of machines. The mechanical spindle, which is often used in the processing of complex aeronautical structures such as titanium alloys, has the characteristics of large torque and impact resistance. However, its long drive chain and complex structure make it difficult to effectively forewarn and diagnose its faults. In this paper, a fault forewarning and diagnosis method is designed, which is based on the analysis of characteristics of vibration time-frequency domain of mechanical spindle. Firstly, a method for calculating the frequency characteristics of key components in the drive chain of mechanical spindle is proposed, and the signal characteristics of vibration are obtained. Secondly, according to the position and layout of each component in the spindle drive chain, the layout scheme of signal acquisition points is designed based on the principle of point-to-surface integration. This scheme ensures that the signals of each point can not only reflect the state of the spindle, but also reflect the vibration characteristics of different parts. Variable speed test is carried out on different equipment of the same type, and the signals processed by Fourier transform, and the frequency domain signals at different speeds are obtained. The time-frequency signal of the spindle is analyzed to find its vibration characteristics. Combining with the results of theoretical calculation, the working state of the spindle and the working performance of each component, as well as the specific fault parts and types of fault are obtained. Through experimental verification, the method proposed in this paper effectively improves the ability of working state monitoring and fault diagnosis of the spindle system.

1. Introduction

CNC machines play an important role in supporting and safeguarding in the development of manufacturing industry. As the core component of CNC machine tool, the spindle’s performance is directly related to the machining performance and accuracy of machine tool [1]. A spindle with good performance can effectively guarantee the quality of part processing. However, in actual processing, failures of the spindle system can be caused by many factors, such as aging and wear of components, unreasonable machining parameters, overload operation, and insufficient cooling and lubrication. Although it does not necessarily stop the machine, there are major safety and processing quality hazards. Therefore, monitoring the performance and status of the spindle is particularly important.

At present, monitoring its vibration, noise and other characteristics is the method commonly used of spindle monitoring by equipment maintenance personnel [2], but there are two defects in this method. First of all, the mechanical spindle is a complex mechanical transmission system, there are many possible parts for failure. It’s hard to locate the specific failure point. Secondly, if significant noise and vibration have occurred, the failure of the spindle is already very serious, and many components may
be failures already. Therefore, the methods and measures which can precisely and effectively monitor spindle’s performance are needed.

In this paper, a fault forewarning and diagnosis method based on the vibration time-frequency signal of spindle system is proposed. By designing a reasonable signal monitoring point, the vibration signal of the whole spindle and each key component is collected. Set the comparison experiment of variable speed and variable equipment, the data is processed by Fourier transform, and the time-frequency signal of the spindle system is analyzed synthetically to find its typical vibration characteristics. Combined with the theoretical calculation and analysis of key component’s vibration, the problem can be quickly and effectively found.

2. The analysis of mechanical spindle’s vibration characteristic
A domestic 5-axis CNC machine uses a mechanical spindle, and its drive chain is long, as shown in Figure 1. It mainly includes the motor, gearbox, drive shaft, bevel gear pair, helical gear pair, coupling and spindle, and every part may fail after long-term use. Due to the long spindle drive chain and the large number of components, faults are difficult to be located. In order to improve the efficiency of maintenance and the utilization of equipment, and avoid removing the precision installed parts in conditions of uncertainty. It’s very important to locate the faults quickly and accurately. In order to determine the faulty components, we must know the vibration signal of each component.

![Diagram of mechanical spindle drive chain of a 5-axis machine tool](image)

**Fig.1. diagram of mechanical spindle drive chain of a 5-axis machine tool**

2.1 Gear vibration analysis
There are two sets of bevel gear pairs and helical gear pairs in the spindle drive chain, which will produce a variety of vibration signals while spindle is running. For the gear transmission system, the calculation method of characteristic frequency is already exist. By analyzing the vibration signal of the gear pair, various faults of the gear transmission can be found out, including wear, overload, eccentricity, backlash migration, teeth rupture, teeth broken and chasing teeth [3]. The GMF (Gear-mesh Frequency) is an important parameter for studying the vibration of the gear. All the gears will produce a Gear-mesh Frequency when meshing. Generally, from whether there is a certain amplitude of side band in the meshing frequency, we can analyze whether the gear transmission effect is good or not [4].

When the gear system is running, the frequency with large amplitude is more related to the GMF, For example, there will be some peak amplitude at GMF, 2GMF, 3GMF and other frequencies [5]. The vibration signal characteristics of gear in common fault state have been studied in detail, For example, when the gear wear is obvious, the sideband of the GMF increases, and the amplitude is always higher at 2GMF and 3GMF. When the gear bear a large load, the amplitude of the GMF is generally large; when the gear is eccentric and there is a backlash, a significant sideband is generated at the gear GMF; when the gear is cracked or broken, a large amplitude will be at the GMF [6].

2.2 Bearing analysis
There are many bearings in the spindle drive chain, which play an important role in the stability of mechanical transmission. However, bearing failure takes a large proportion in the traditional mechanical failure, bearing wear, corrosion, breakdown and other faults have a large impact on the transmission of the mechanical system, and always accompanied by varying degrees of vibration.
The "characteristic frequency" of bearing has been deeply studied by scholars, so this paper will not elaborate it in detail. The calculation formula of characteristic frequency of bearing fault is shown in Table 1 [7]. Where, $D$ is the bearing diameter corresponding to the roller center; $d$ is the diameter of the bearing roller; $Z$ is the number of rollers in the bearing; $\alpha$ is the contact angle; $f_i$ is the rotation frequency of the inner race of the bearing.

Table 1. Calculation formula of bearing characteristic frequency

| Bearing parts          | Calculation formula                                       |
|------------------------|-----------------------------------------------------------|
| Inner race raceway     | $f_{bpf_i} = \frac{-Zf_i(1+(d/D)\cos \alpha)}{2}$        |
| Outer race raceway     | $f_{bpf_o} = \frac{-Zf_i(1-(d/D)\cos \alpha)}{2}$        |
| Cage                   | $f_c = \frac{f_i(1-(d/D)\cos \alpha)}{2}$                |
| Roller                 | $f_{bsf} = \frac{-f_i D}{2d} \left(1-(\frac{D}{d}\cos \alpha)^2\right)$ |

3. Vibration analysis experiment of key parts of spindle

Since the mechanical spindle has a long drive chain and many components, it is difficult to diagnose and locate faults. At present, the common method is to check the bearing, gear and other parts in turn after removal, and find the fault point by means of troubleshooting. This method is time-consuming and labor-intensive, and for some precision-mounted components, it will seriously affect the transmission accuracy and effect after disassembly. In this paper, a new method is proposed. First of all, the vibration detection experiment of each component is needed.

In order to accurately collect the vibration signals of the various components in spindle system, the layout of the collection points should be close to each measured component, and the collecting direction of components such as helical gears should be concentrated in the axial direction of the gears. However, the spindle drive chain is mainly distributed inside the spindle box and cannot be directly measured. Therefore, according to the main position layout of each key component in the spindle drive chain and the allowable conditions of the experimental equipment, three measuring points are selected for measuring the vibration outside of the spindle box by the comprehensive action of each part. The position of three measuring points on the spindle is shown in Fig. 3.
Point 1 is set at the end of the spindle, which mainly monitors the actual vibration of the spindle head. Point 2 is set on the side of the spindle box, because there are many gears running here. Point 3 is set at the back-end of the spindle box, which mainly reflect the influence of the vibration of the motor and gearbox on the spindle system.

By comparing the vibration signals of two machines at the same acquisition point and the same speed, the state performance of two machines can be diagnosed, as well as the main contribution parts of each machine’s vibration. Comparing the vibration signals of the same collection point at different speeds of a single machine, it can be known whether the vibration mainly comes from the front or the back of the spindle. And the performance at high and low speeds.

3.1 Vibration experiment design
In order to ensure the authenticity and reliability of the measured vibration data, equipment comparison and speed comparison experiments are implemented. In equipment comparison experiment, we will collect and compare the vibration signals of two machines which belong to the same type, installed at the same time, under the same working condition and experimental conditions. The speed comparison experiment was carried out by using a same input motor speed and changing the output speed for comparison.

The spindle drive chain is shifted by gearbox. In order to make sure whether the main vibration of the spindle system comes from the front spindle or the motor and gearbox, in the experiment, the motor will keep a same speed and spindle work in high and low gear respectively. The transmission ratio of the machine in the high and low gear position is $i_1 = 0.2266$ and $i_2 = 1.323$, when the speed is lower than 800rpm and the low gear is used. When the speed is higher than 1200rpm, the high gear is used, when the speed is between 800~1200rpm, the shift is not adopted.

In order to distinguish the main contribution points of vibration signals, the test is carried out by switching to high and low gears respectively under the condition of ensuring the same motor speed. After calculation, take the motor speed $N_0 = 2000$ rpm, at this time, the output speed of the spindle c is 453 rpm and 2646 rpm when working in high and low gear.

| machine  | Rotating speed/rpm |
|----------|-------------------|
| Machine 1 | 453               |
| machine 2 | 453               |
|          | 2646              |
|          | 2646              |

3.2 Vibration data analysis
According to the calculation of the rotation speed of the parts in spindle system, and in order to ensure the accuracy of data acquisition, the sampling frequency $f = 1000$Hz is taken, and the vibration signals of three points are collected by the vibration sensors. Finally, Fourier transform is carried out to analyze the vibration signals.
3.2.1 Variable machine experiment

The experiment set at a speed of 453 rpm. The vibration characteristic frequency of the bearing and each gear in the spindle drive chain is calculated, as shown in Table 3.

Table 3: Vibration characteristic frequency of bearings and gears in spindle system

| Spindle components | Parameter characteristics | Vibration frequency/Hz |
|--------------------|---------------------------|------------------------|
| Bevel gear         | $Z_1=36$, $n=453$ rpm    | $f_{m1}=271.8$         |
| Small helical gear | $Z_2=36$, $n=453$ rpm    | $f_{m2}=271.8$         |
| Large helical gear | $Z_3=46$, $n=354.5$ rpm  | $f_{m3}=271.8$         |

bearing outer ring: $D=78$ mm, $d=15$ mm, $\alpha=25^\circ$, $Z=11$; $f_{pbf}=48.76$

bearing inner ring: $D=78$ mm, $d=15$ mm, $\alpha=25^\circ$, $Z=11$; $f_{pfi}=34.28$

Cage: $D=78$ mm, $d=15$ mm, $\alpha=25^\circ$, $Z=11$; $f_c=3.12$

Bearing roller: $D=78$ mm, $d=15$ mm, $\alpha=25^\circ$, $Z=11$; $f_{r0}=691.15$

Fourier transform is performed on the vibration signals of the three points of two machines, in order to get the time-frequency characteristics, as shown in Fig. 4.

![Time-frequency characteristics of vibration signals](image)

Fig. 4. Time-frequency characteristics of vibration signals at three points on two machines at 453 rpm

A comprehensive analysis of Figure 4 shows that the vibration characteristics of the two machines have many in common. For example, the vibration of the point 2 in the two machines is more obvious than the other two points, it means the vibration of the gear transmission on the side of the spindle box is more pronounced than the spindle head and the rear drive. There is a certain commonality between the two, that is, a high amplitude at 100 Hz and 800 Hz.

In addition, the vibration signals of the two machines also have a certain difference, which represents the difference in performance and state of the spindle system of the two machines. Firstly, the overall amplitude of machine 1 is smaller and more uniform than that of machine 2; the overall amplitude of machine 2 is larger and more regular. Through time domain graph analysis, its period $T\approx 170$ ms, and
its vibration frequency is 353Hz, which is close to the rotating frequency of the large helical gear, so it could be speculated that the periodic vibration is mainly generated by the rotation of large helical gear. Among the three groups of vibration signals of machine 1, there is a large amplitude at 100Hz, which is exactly 2 times of the vibration frequency of the outer ring of angular contact ball bearing. Therefore, several groups of angular contact ball bearings in machine 1 are likely to have problems such as wear, which need to be checked in time. However, the amplitude of the machine 2 has a large amplitude at 100 Hz, but the amplitude at the point 2 and point 3 is relatively small, indicating that there is a problem with the front bearing of the machine 2 and the rear bearing is in a good state. The amplitudes of the two machines are large at 800Hz, and it can be seen from table 2 that the frequency is just at 3GMF of the gear transmission system, indicating that the gear transmission system has certain wear. In addition, point 3 of machine 2 has a large amplitude at 200Hz, 270Hz, 900Hz, etc. Indicating that the rear end of machine 2 has a more obvious impact on the vibration of the spindle system, and the parts such as the motor and the gearbox should be checked in time.

3.3.2 Variable speed experiment

According to the experimental scheme, the two machines are analyzed separately, and the experiments were carried out at 453 rpm and 3646 rpm respectively. Comparing the vibration signals of different rotating speeds of a machine can effectively analyze the main contribution sources of vibration, and the performance of the spindle at high and low speed. Fourier transform is performed on the measured experimental data to obtain its frequency domain features, as shown in Fig. 5 and Fig. 6.

**Fig. 5 Time-frequency characteristics of vibration signals of machine 1 at 453 rpm and 2646 rpm**

By comparing and analyzing the time-frequency characteristics of the vibration of the machine 1 at two speeds, the high amplitudes at 100 Hz and 800 Hz are found when \( n = 453 \text{ rpm} \). However, when \( n = 2646 \text{ rpm} \), the higher amplitude value is also obtained at 410Hz, especially at points 2 and 3. It is calculated that the frequency is exactly 2 times of the vibration frequency of the inner ring of the bearing, so the bearing of the front and rear bevel gears has strong vibration when running at high speed, and the inner ring of the bearing may have problems such as wear and even sintering. The vibration signal of point 2 has a high amplitude in the high frequency range. Due to the large number of components at point 2, and the vibration frequency of each component is different. Therefore, when the vibration of many components is obvious, the phenomenon of concentrated high amplitude appears as shown in Figure 5.
The time-frequency characteristics at different rotating speeds of machine 2 are compared and analyzed. The difference between high and low speed is similar to that of machine 1, and there are concentrated high amplitude values at point 2. However, the vibration characteristics of point 1 and point 3 have changed. The high amplitude appears at about 560 Hz. It is twice the vibration frequency of the outer ring of the bearing. So, it can be inferred that the front and rear bearings of equipment 2 have abnormal vibration, and the failure point lies in the outer ring of the bearing.

4. Conclusion
The vibration signals of different parts of the spindle are collected by setting the speed and machine comparison experiments. The Fourier transform is performed on the vibration data, and the time-frequency characteristics are analyzed to find the main vibration frequency. Compare the results with the theoretical calculation values of the vibration frequency of each component. And the state of the spindle system and the parts with wear and other faults can be effectively judged.

The vibration of the side gear transmission part is more violent than the front and rear ends of the spindle system. From the analysis of the frequency domain diagram, the main vibration is caused by bearings regardless of the equipment and speed, especially the installation position of the bevel gears. Therefore, as the most vulnerable part of the whole spindle system, the bevel gear’s bearings should be maintained to ensure good lubrication. The helical gears on the side of spindle box also need to be attention because of the significant vibration at low speed.

The results show that the spindle system fault warning and diagnosis method based on the mechanical spindle time-frequency domain analysis can effectively detect the working performance and state of the spindle, and it is also helpful for locating specific fault parts. It has a great value in engineering application.

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