



Detection and visualization of chatter in gear hobbing based on combination of time and frequency domain analysis

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Abstract

This paper presents a method for the detection and visualization of chatter in gear hobbing based on a combination of time and frequency domain analysis of acceleration data. By analyzing the acceleration data of the workpiece rotation shaft, chatter was identified, and the relationship between the vibration of the workpiece rotation shaft of hobbing machine and profile deviation of machined gears was established. First, a hobbing cutting experiment was made with different cutting parameters; meanwhile, DH5922N dynamic signal test analysis system and DH311E acceleration sensors were used to collect acceleration data during the hobbing process. Then, the relationship between tooth passing frequency and chatter was established by time domain and frequency domain analyses; furthermore, variance and root mean square value of acceleration data were calculated to judge the magnitude of data fluctuation to indirectly reflect the stability of the machining process. Finally, by detecting the tooth profile deviation and analyzing surface topographies of machined gears, the relationship between vibration and gear machining quality was established: low vibrational level leads to better gear machining precision and surface topography. The research result can provide a theoretical basis for the accurate selection of machining parameters and excellent structural design of hobbing machine tools.

Keywords Gear hobbing · Workpiece rotation shaft vibration · Time and frequency domain analysis · Chatter · Surface topography

1 Introduction

As the core mechanical parts, gears are widely used in industries and other fields such as automobiles, ships, aerospace, high-speed rail, energy equipment, and intelligent manufacturing. The quality and performance of gears determine the performance and reliability of equipment, and the gear industry has become the largest part of the general mechanical field. Gear hobbing is used as a rough or semi-finishing process for gears; hobbing is more efficient than other processing technologies (such as gear shaping), so gear hobbing machine tools are widely used, and the number of hobbing machines currently accounts for 45–50% of

the total number. As a rough machining process, hobbing gear's axial feedrate and radial cutting depth are large. It is difficult for a machine tool with poor rigidity and unreasonable structural design to ensure the machining precision of the hobbing machine. Therefore, improving the stability and processing precision of the hobbing machine, reducing gear production costs, and simplifying gear processing procedures are of great significance to the development of the gear processing industry.

Hobbing is a dynamic process with intermittent machining, which generates a periodic cutting force between the hob and the workpiece, causing the machine to vibrate. Machine tool vibration can be mainly divided into two categories, forced vibration and regenerative vibration. Forced vibration is caused by repeated impacts of hob teeth on the surface of the workpiece during hobbing machining, and this phenomenon is unavoidable [1]. Regenerative vibration is also known as chatter. There are several forms of chatter like thermo-mechanical chatter, frictional chatter, mode coupling chatter, and regenerative chatter, and regenerative chatter is the most common form of self-excited vibration. Regenerative vibration originates from the self-excitation mechanism in the

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hobbing process [2]. At first, the hob-workpiece system is excited by the cutting force to vibrate and finally generates a wavy surface when the cutting edge removes material. Then, the current wavy surface is cut by the next cutting edge, which will also leave a new wavy surface on the new cutting area. This process is repeated until the end of the cutting. Vibration during gear processing will reduce the surface quality and precision of the gear, causing hob wear or even break. The occurrence of chatter should be avoided to make the machine tools get higher performance [3, 4].

At present, many scholars have conducted in-depth research on chatter. Li et al. [5] established the vibration response function model of the hob spindle in the X direction and obtained the hob spindle vibration frequency, vibration acceleration, and displacement data curve. Lei et al. [6] adopted the vibration resonance response analysis method to obtain the vibration response law of the hob spindle system (HSS); the obtained vibration response rule can guide the optimization of machining parameters of the high-speed dry-cut hob spindle system. Altintas et al. [7] studied the milling process and found that when the impact frequency of cutter teeth and the natural frequency of tool bar are close, the chatter phenomenon disappears in the milling process, and the machine tool is in a stable milling process. Sant'Anna et al. [8] did research on chatter in hobbing, analyzed the mechanism of chatter in hobbing, compared the productivity of the hobbing machine under different cutting conditions, and finally verified the stable cutting conditions of hobbing.

This paper mainly studied the influence of hob rotation speed on chatter, and many scholars had made in-depth research on the effect of tool speed on chatter suppression. E. Soliman et al. [9] managed to judge the occurrence of chatter by using R statistical value extracted from the cutting force value and developed a system to suppress milling chatter. Ding et al. [10, 11] proposed an active chatter suppression strategy that simultaneously adjusted the amplitude and frequency of the spindle speed by studying adaptive chatter suppression for turning. Liu et al. [12] presented a reliable technique in the study to detect chatter in gear grinding process based on servo feed motor current and wavelet packet transform.

However, hobbing has its characteristics; the hob and the workpiece maintain a strict generating relationship during

processing, and whether the traditional vibration suppression methods and conclusions are valid in the hobbing machine are currently less studied.

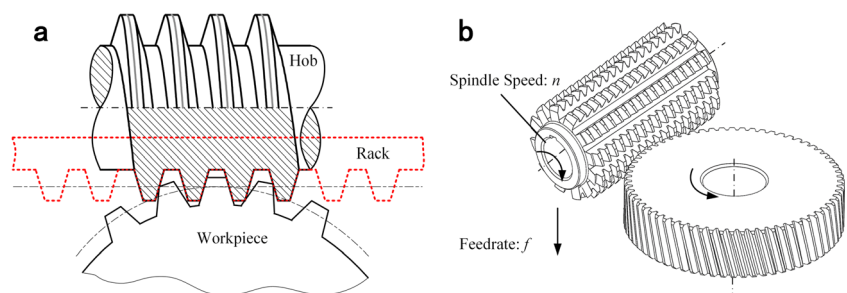
In this study, DH311E acceleration sensors were used to collect vibration data during hobbing processing. First, natural frequencies of the workpiece rotation shaft were obtained through the hammer test. Then, the hob rotation speed corresponding to the natural frequency was calculated according to stable cutting conditions. Furthermore, in the experimental stage, the time spectrum and the frequency spectrum of vibration data were analyzed to determine whether chatter vibration occurred and record the chatter frequency simultaneously. Finally, the gear measuring center was used to detect the machining precision of gears to obtain the optimal spindle speed for hobbing. By analyzing the acceleration data through this method, chatter was detected and visualized during machining.

It is of great significance to suppress the vibration of the hobbing machine and improve the machining precision of gears. At the same time, this method is more conducive to promote and use in the gear industry because of its economic benefits.

2 Hobbing machining vibration

The hobbing process is mainly conducted based on the principle of worm and worm wheel meshing [13, 14]. The hob is equivalent to a worm, and the cutting edge is formed by slotting and relief machining, as shown in Fig. 1a. During the process of hobbing, the hob and the workpiece make a generating motion at a certain speed ratio, and at the same time, it performs an axial feed motion relative to the full tooth width of the workpiece, and those motions are illustrated in Fig. 1b. Gear hobbing is machining gears based on a principle of the generating method, and the tooth profile is the envelope of the trajectory of cutting edges. Theoretically, by adjusting the meshing speed ratio and ensuring the conjugate relationship between the hob and the gear blank, gears with the same module and different teeth numbers can be processed [15, 16].

Fig. 1 Schematic diagram of the hobbing machine: (a) Principle of meshing between hob and gear, (b) motion relationship between hob and gear



The cutting process of the hob is equivalent to the meshing process of a pair of space shaft gears. The hobbing system can be simplified as a spring-mass-damper vibration system with two degrees of freedom in the X and Y directions, as shown in Fig. 2b. During the chip generation process, the cutting force is related to the rotation angle of the hob which can be understood through the instant chip thickness variation phenomenon, and the rotation angle of hob is a function of the cutting time that can be described as $\alpha_R = \frac{\pi mt}{30}$ ($0 \leq \alpha \leq \alpha_{RMAX}$), and the dynamic hobbing force can be expressed by $F(\alpha_R)$. So the mathematical model of dynamic hobbing process with four degrees of freedom can be expressed by Eq. (1):

$$\begin{cases} m_1 \ddot{x}_1 + c_{x1} \dot{x}_1 + k_{x1} x_1 = F_x(\alpha_R) \\ m_1 \ddot{y}_1 + c_{y1} \dot{y}_1 + k_{y1} y_1 = F_y(\alpha_R) \\ m_2 \ddot{x}_2 + c_{x2} \dot{x}_2 + k_{x2} x_2 = -F_x(\alpha_R) \\ m_2 \ddot{y}_2 + c_{y2} \dot{y}_2 + k_{y2} y_2 = -F_y(\alpha_R) \end{cases} \quad (1)$$

where x_j and y_j ($j = 1, 2$) respectively represent the displacement of the hob and workpiece along the X and Y directions. c_{ij} , k_{ij} , m_j ($i = x, y; j = 1, 2$) are the damping, stiffness, and masses coefficients of the cutting system, respectively; and the subscripts can be used to determine whether it belongs to the hob or the workpiece system and in which direction. Equation (1) represents the theoretical formula for the vibration of the Z -axis tangential section of the hob-workpiece system along the X - and Y -axis. It can intuitively express the time-varying characteristics of the cutting force caused by the dynamic change of the chip thickness and also provide a theoretical basis for the following research.

Based on the above analysis, this study used acceleration sensors to detect the acceleration data of the workpiece rotation shaft and analyzed the state of the hob [17–19]. Considering the requirements of installation method, frequency range, and sensitivity, DH311E sensors (produced by Donghua Testing Technology Co., Ltd., China) were used in the study [20–22].

3 Experimental setup

The main vibration source in this study is the impact of cutter teeth on the workpiece surface when the hob is cutting the workpiece. Hiromitsu studied the relationship between chatter and tooth passing frequency in milling and found that when the tooth passing frequency is close to the natural frequency of the milling cutter, the cutting process is stable; when the two frequencies are not close, chatter will occur during machining [22]. Because of the differences in the structure of the milling cutter and the hob, in addition to first tooth passing frequency f_1 mentioned by Hiromitsu, there exists another passing frequency during the hobbing process which can be called as second tooth passing frequency f_2 , as shown in Fig. 3 [8].

First tooth passing frequency is the passing frequency of two teeth on the section of hob cutting the same tooth space of the workpiece. The frequency is related to the number of hob gashes z and the rotation speed n of the hob, as shown in Eq. (2).

$$f_1 = \frac{z \cdot n}{60} \quad (2)$$

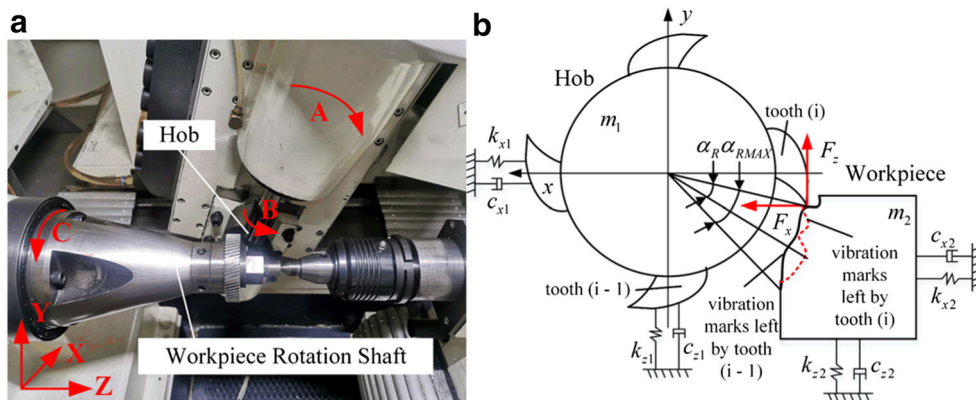
Teeth of the hob are evenly distributed on the helix, so in addition to first tooth passing frequency, adjacent teeth on the same gash will participate in cutting in sequence along the axis of the hob, resulting in a second type of passing frequency. When the structure of the hob is determined, the passing frequency of hobbing can be calculated according to Eqs. (3) and (4).

$$h = p \cdot \sin \gamma \quad (3)$$

$$f_2 = \frac{n \pi R}{30h} \quad (4)$$

When the passing frequency of teeth is close to the natural frequency of workpiece rotation shaft, the phase difference between two wavy surfaces generated by tooth (i) and tooth ($i - 1$) is close to 0, and the thickness of cutting chips is constant. According to Eqs. (3) and (4), linear relationship between impact frequency and hob rotation speed is maintained,

Fig. 2 Coordinate and dynamic model of the hobbing machine: (a) schematic diagram of hob-to-workpiece shaft system and 6 motion axes, (b) dynamic model of hobbing machining



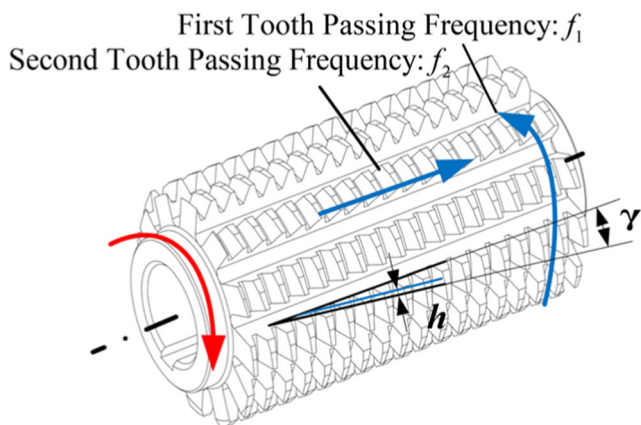


Fig. 3 Frequency direction of the first and second tooth passing frequency of the hob

so it is necessary to get the natural frequency of workpiece rotation shaft first. The frequency response function obtained through the hammer test is shown in Fig. 4. The first natural frequency of the workpiece rotation shaft is 414.8 Hz.

Geometric parameters of the hob used in this research, the safe rotation speed range of hob, and calculated tooth frequency range are presented in Table 1 and Table 2, respectively. According to the structural rigidity of the machine and the performance of the motor, the optimal speed range of hob is 1600–2500 rpm to ensure the safety and efficiency of the machine. Generally, for low-speed hobbing (the speed is less than 500 rpm), the first tooth passing frequency is small, and the natural frequency of the workpiece rotation shaft or hob rotation shaft is greatly different, so stable cutting cannot be formed. However, for the machine used in the study, the frequency range of first tooth passing frequency f_1 calculated by Eq. (2) is 320–500 Hz, so first tooth passing frequency can also stabilize the machining process.

On the other hand, the frequency range of f_2 calculated by Eqs. (3) and (4) is 24,800–38,750 Hz. High-frequency vibration is difficult to transfer energy in the mechanical structure, so the second tooth passing frequency cannot be taken into account. In summary, when the machining process is stable, the first tooth pass frequency f_1 is close to the first-order

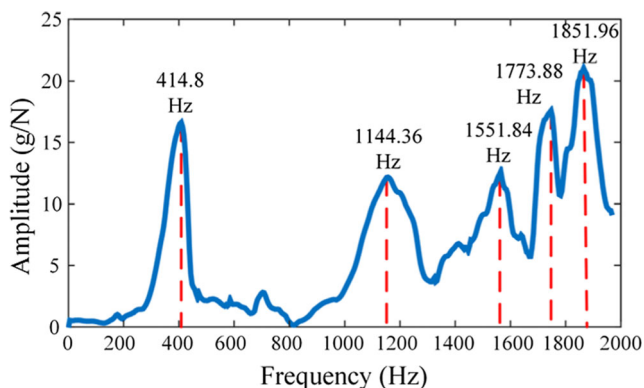


Fig. 4 Frequency response function of the workpiece rotation shaft

Table 1 Geometric parameters of the hob

| Parameters | Specifications |
|-----------------------------------|----------------|
| Helix angle γ ($^\circ$) | 1.97 |
| Number of gash z | 12 |
| Axial pitch p (mm) | 3.14 |
| Height between columns h (mm) | 0.108 |
| Outer diameter of hob R (mm) | 16 |

natural frequency of the workpiece rotation shaft of the hobbing machine, and the relative rotation speed of the hob is calculated by Eq. (2) and rounded to 2100 rpm.

This paper mainly studied the influence of tooth passing frequency on hobbing machining vibration. The feedrate and radial cutting depth of the workpiece of cutting were set to 8 mm/min and 0.3 mm, 10 mm/min and 0.5 mm, and 12 mm/min and 0.7 mm, respectively. The hob rotation speed was set to 1800 rpm, 2100 rpm, and 2400 rpm, respectively. Table 3 shows the specific experimental parameter design of nine tests.

YGS3160B (produced by Zhejiang Jiaxue CNC Machine Tool Co., Ltd., China) hobbing machine was used for the cutting experiment. At the same time, DH311E acceleration sensors were installed to collect vibration data during processing. The sampling frequency was set to 5000 Hz. The parameters of processed gears are shown in Table 4.

The hobbing machine used in this experiment needs cooling fluid during processing, so acceleration sensors should not be too close to the cutting processing area to avoid the impact of cutting fluid splash on measurement results. Meanwhile, to protect the acceleration sensors, a sealing film must be wrapped at the wiring port of sensors to prevent cutting fluid from affecting the accuracy of sensors. Finally, before the completion of the experiment, it is necessary to ensure that the installation position of acceleration sensors remains unchanged to prevent changes at signal acquisition point from affecting collected data. The actual processing figure is shown in Fig. 5.

4 Results and discussion

This gear machining experiment was performed according to experimental parameters in Table 2. During the machining

Table 2 Safe rotation speed range and calculated tooth frequency range

| | |
|-------------------------------------|---------------|
| Safe rotation speed range n (rpm) | 1600–2500 |
| Calculated f_1 range (Hz) | 320–500 |
| Calculated f_2 range (Hz) | 24,800–38,750 |

Table 3 Parameter design of nine tests

| Test | Rotation speed n (rpm) | Feedrate f (mm/min) | Radical cutting depth a_p (mm) |
|------|--------------------------|-----------------------|----------------------------------|
| 1 | 1800 | 8 | 0.3 |
| 2 | 1800 | 10 | 0.5 |
| 3 | 1800 | 12 | 0.7 |
| 4 | 2100 | 8 | 0.3 |
| 5 | 2100 | 10 | 0.5 |
| 6 | 2100 | 12 | 0.7 |
| 7 | 2400 | 8 | 0.3 |
| 8 | 2400 | 10 | 0.5 |
| 9 | 2400 | 12 | 0.7 |

process, DHDAS (DongHua Dynamic Analysis System, produced by Donghua Testing Technology Co., Ltd., China) based on the DH5922N dynamic signal test hardware platform was used to record acceleration data. Cutting of the total tooth height of gears was divided into three machining processes, and the effect of vibration on gear machining accuracy during gear hobbing was studied. This was mainly achieved by controlling the cutting depth in the third machining process which machined the final tooth surface. In this experiment, a total of four measurement points in the X , Y , and Z directions were collected.

The status of the hob-workpiece system in the cutting process is as shown in the following figure. Figure 6a presents the hobbing status; Fig. 6b–e show the normal chip generation process, and the undesired status comes from the displacement along X , Y , and Z directions respectively which will decrease the geometric precision of gears. Gear deviations are mainly divided into three categories: pitch deviation, tooth profile deviation, and helix deviation. The existence of total profile deviation F_α will significantly decrease the accuracy and stability of the gear transmission. Therefore, F_α is used as a metric to measure the influence of chatter on gears. The hob feeds along the axis of the workpiece rotation shaft. Taking into account the stability of the clamping, vibration will not produce large displacement and affect the tooth profile deviation. Besides, the displacement caused by the X -axis vibration is mainly reflected in the radial comprehensive error F_i' of

Table 4 Gear processing parameters

| Parameters | Specifications |
|-----------------------------|----------------|
| Module m (mm) | 1 |
| Pressure angle α (°) | 20 |
| Tooth number z | 65 |
| Outer diameter r (mm) | 34.5 |
| Inner diameter r_1 (mm) | 10 |

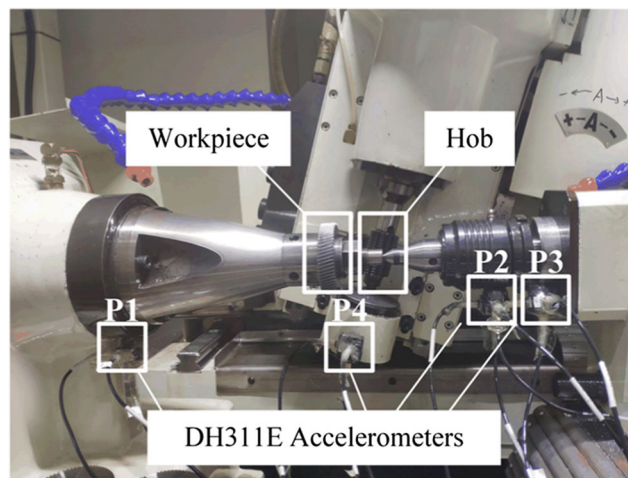


Fig. 5 Experimental processing environment

gears, which have little effect on the tooth profile deviation. On the contrary, the vibration of the tooth along the Y direction will directly increase F_α .

On the other hand, mean values of positive vibration acceleration of the workpiece along X , Y , and Z directions during the three cutting processes of the hob at the same measuring point in the first test were calculated. It is obvious that the amplitude of the acceleration of the Y axis is greater than the X and Z axis, and mean values are larger too, as shown in Fig. 7.

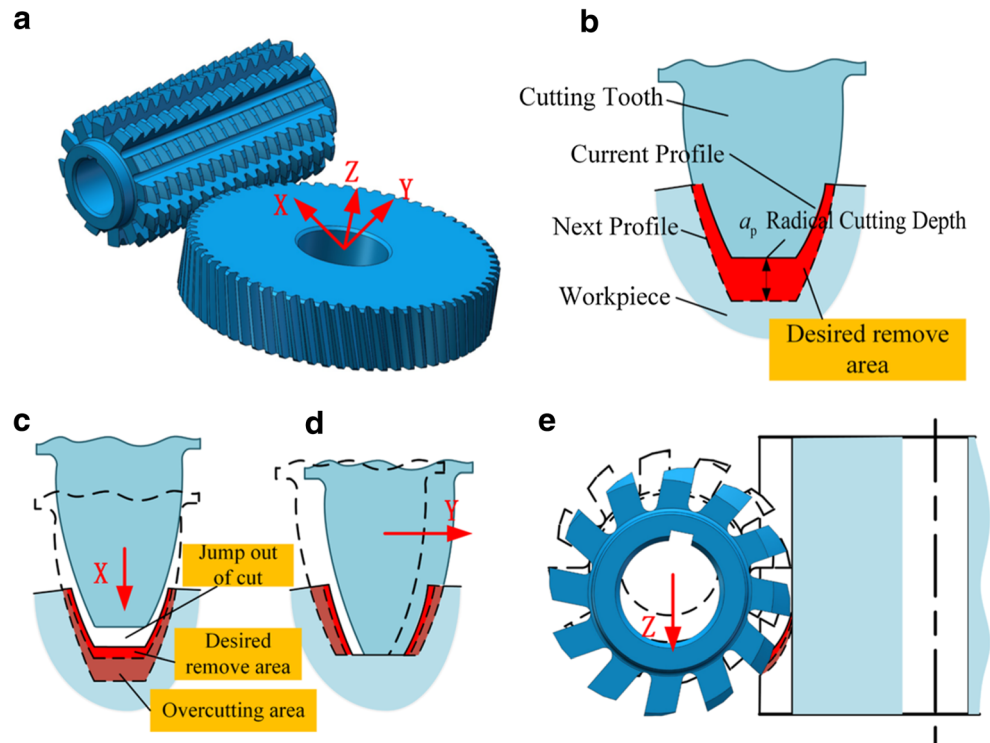
Finally, through the above analysis, the vibration data in the Y direction at the second point was selected for data analysis, as shown in Fig. 8.

Vibration analysis was mainly performed from two aspects: The first was to determine the magnitude of the vibration by analyzing the amplitude changes of acceleration collected during the machining process. The second one was to analyze whether there were characteristic frequencies (chatter f_c in most cases) in addition to the tooth passing frequency f_t and its harmonic components, frequency analysis was performed through the Fast Fourier Transform (FFT).

4.1 Time domain analysis of acceleration data

This study mainly considered the influence of the hob rotation speed on the vibration. In the hobbing process, the cutting volume of a single tooth and corresponding cutting force will decrease with constant feedrate and increasing rotation speed of the hob [23]. According to the linear relationship between the cutting force and acceleration, vibration acceleration also decreases as the speed increases. However, as shown in Fig. 8a, as the hob rotation speed n increased from 1800 to 2100 rpm with the same feedrate and radial cutting depth, the acceleration amplitude of the workpiece rotation shaft was the smallest, and the average value was 3.7 g; but when the rotation speed was set up to 2400 rpm, vibration amplitude

Fig. 6 Influence of vibration in different directions on tooth profile deviation: (a) schematic diagram of hobbing, (b) chip removed by tooth normally, (c) vibration of the tooth along the X direction, (d) vibration of the tooth along the Y direction, (e) vibration of the tooth along the Z direction



came to a maximum with an average of 8.1 g. As shown in Fig. 8b and c, when the hob speed increased, the amplitude of the acceleration also kept the same change law.

The statistical parameters reflecting the vibration level indicator are widely used in time domain waveform analysis. This study used two time-domain statistical parameters as variance value (VAR) and root mean square value (RMS) to reflect the workpiece vibration degree at different speeds. The variance value and root mean square value of the vibration acceleration under different working conditions are shown in Fig. 9. The feedrate and radial cutting depth were constant to every single polygonal line. As the rotation speed increased, the VAR and RMS values of the acceleration also decreased first and then increased reflecting the sharp fluctuation of cutting force during cutting. On the one hand,

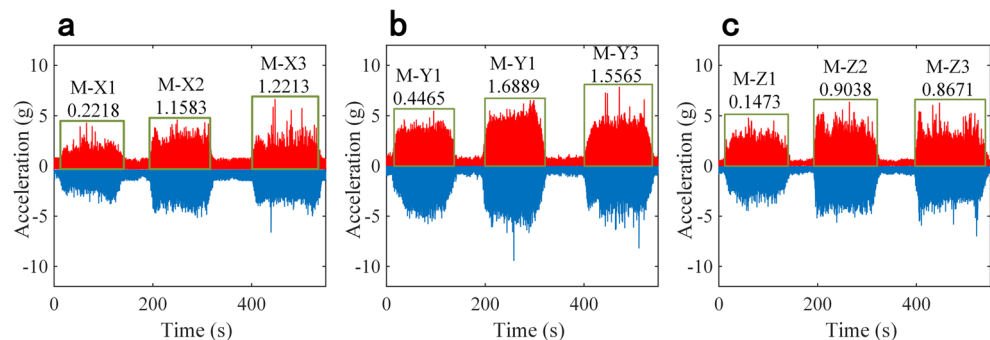
machining vibration will affect the precision of the gear, which not only reduces the production efficiency but also may cause material waste and decrease the life of the machine.

It can be concluded that 2100 rpm is the optimal hob rotation speed through time-domain analysis of the vibration data; the amplitude and fluctuation of the vibration acceleration are small in this condition, which will not cause excessive significant impact on the machine tool.

4.2 Frequency domain analysis of acceleration data

Frequency domain analysis is a universal method of signal analysis, and the spectrum is an important feature in terms of frequency which reflects the frequency components and distribution of the signal. When the hob tooth passing frequency

Fig. 7 Acceleration data along X , Y , and Z direction in the first test and the mean values of three cutting processes



Note: M-X1 means the mean value of acceleration data of the first cutting process in X direction, other values keep the similar principle.

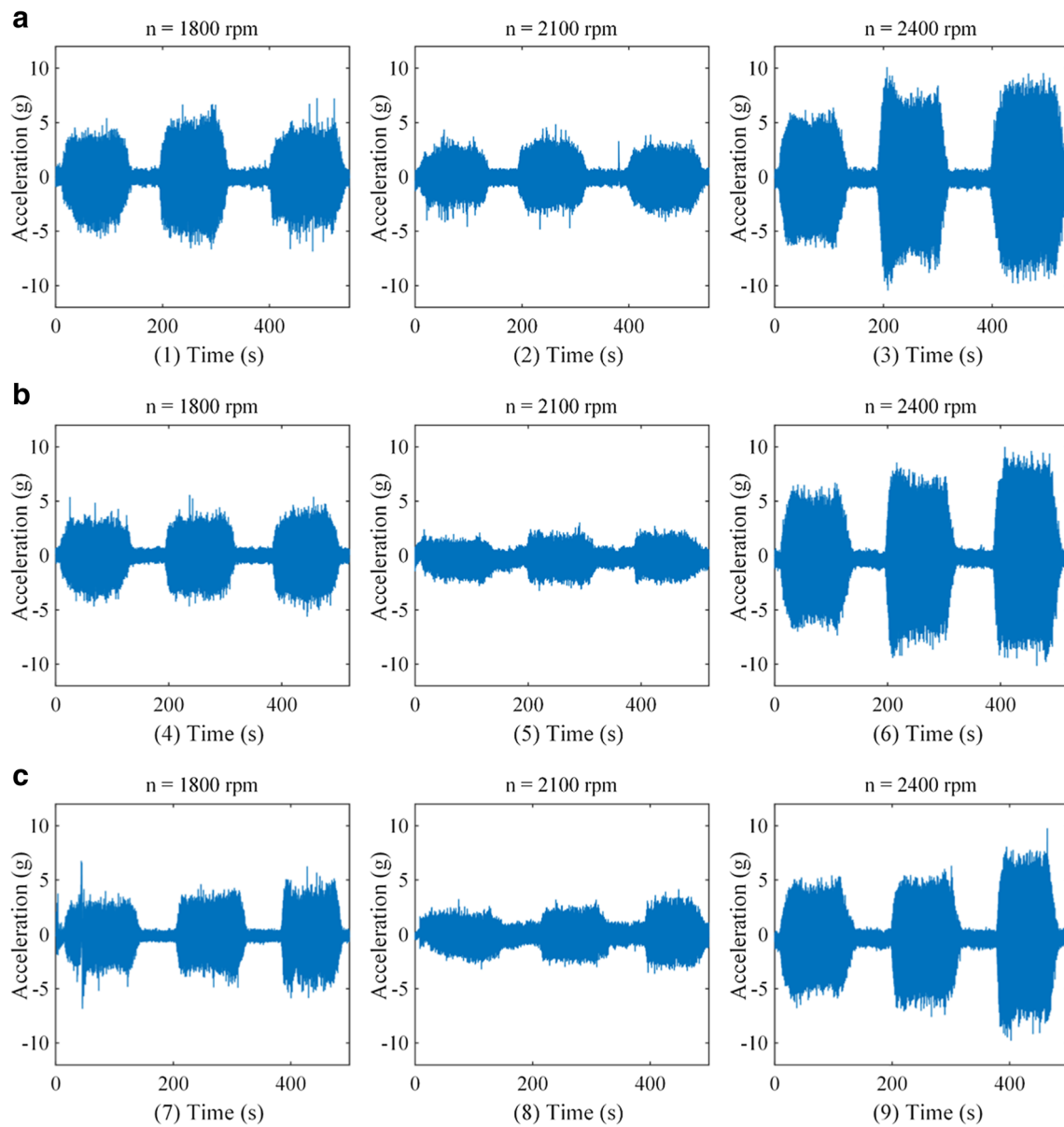
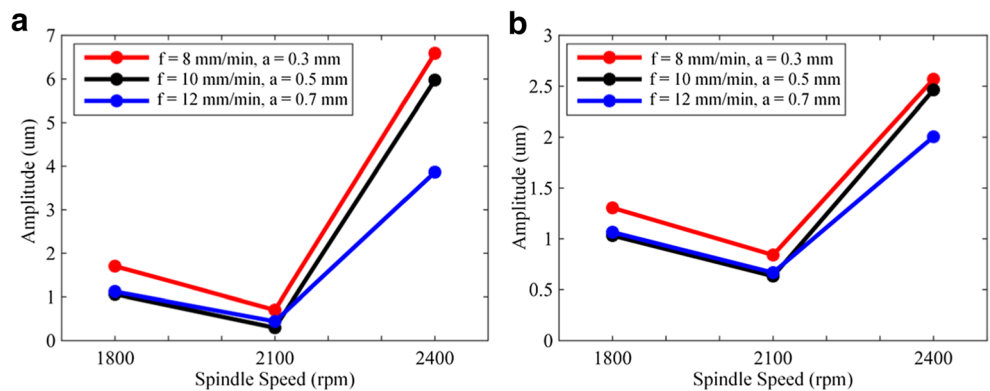


Fig. 8 Time domain diagram of acceleration of workpiece rotation shaft in the Y direction with different cutting parameters: (a) $f = 8$ mm/min, $a_p = 0.3$ mm; (b) $f = 10$ mm/min, $a_p = 0.5$ mm; (c) $f = 12$ mm/min, $a_p = 0.7$ mm

Fig. 9 Variance and root mean square values of vibration acceleration under different working conditions: (a) variance value (VAR), (b) root mean square value (RMS)



was close to natural frequency of the workpiece rotation shaft, the amplitude of each frequency component was small, and there was no chatter frequency component besides the tooth passing frequency and its harmonics which showed stable cutting. When they are not close, chatter appears with a large amplitude of each frequency component. In this experiment, the FFT method was used to perform a frequency domain analysis of the hobbing vibration data. Frequency domain analysis differed from time domain analysis which is the study of acceleration amplitude changes throughout the machining process, the former analytical method mainly studied the third feed motion under different working conditions. For 9 machining tests, there were three feedrates such as 8 mm/min, 10 mm/min, and 12 mm/min; the corresponding processing time was 540 s, 520 s, and 500 s. When hob started the third cutting, frequency components were analyzed with 2048 extracted data points from the normal cutting period.

This study first analyzed the frequency components of the acceleration data when the cutting fluid was turned on and the hob was idling, as shown in Fig. 10. In the experiment, the rotation speeds of hob were set as 1800 rpm, 2100 rpm, and 2400 rpm. The corresponding passing frequency of the cutter teeth was calculated as 360 Hz, 420 Hz, and 480 Hz by Eq. (2). It was obvious that when the hob was idling without cutting, the frequency signal of the machine tool is mainly concentrated around 300 Hz which was less than 360 Hz, with smaller acceleration amplitude. This type of frequency signal can be regarded as a machine interference frequency during analyzing the frequency component of the machining process.

When $n = 1800$ rpm, $f = 8$ mm/min, and $a_p = 0.3$ mm, the vibration spectrum is shown in Fig. 11. The tooth pass frequency is 360 Hz, which is not close to the natural frequency of the workpiece rotation shaft, in the frequency range of 0–2000 Hz. In addition to the cutting frequency (360 Hz) and other 4 harmonics (720 Hz, 1080 Hz, 1440 Hz, 1800 Hz), a large acceleration peak appeared at the

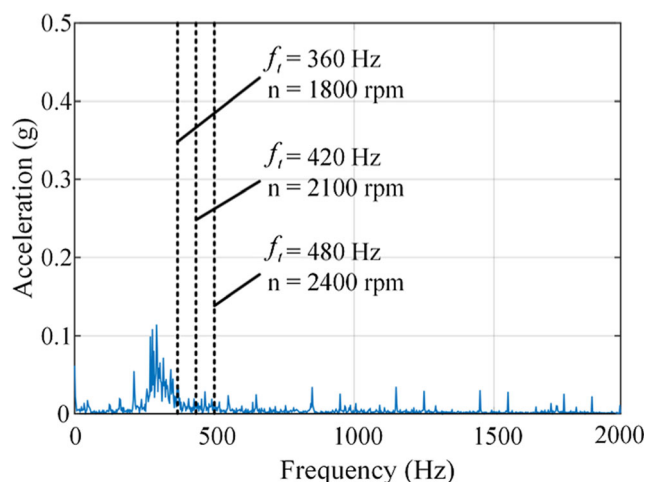


Fig. 10 Frequency components in an idling condition

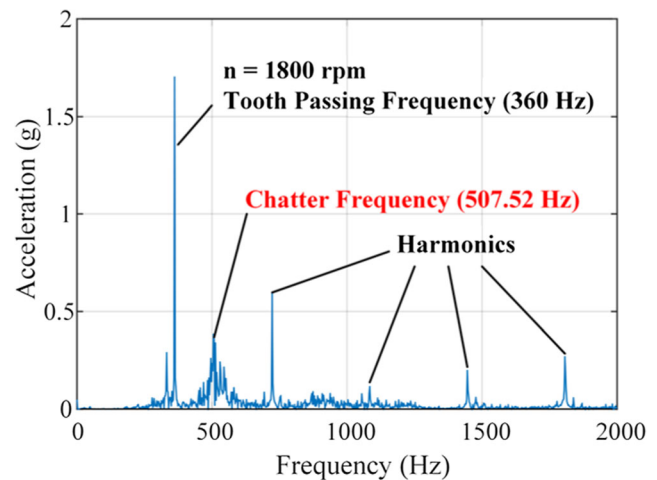


Fig. 11 Cutting vibration spectrum when $n = 1800$ rpm, $f = 10$ mm/min, and $a_p = 0.5$ mm

frequency of 507.52 Hz, indicating the occurrence of chatter in this working condition.

The frequency spectrum of the whole experiment is shown in Fig. 12. When the feedrate and the radial cutting depth remained the same values, the acceleration spectrum showed the same change law with different hob rotation speeds. In summary, when the hob speed was 1800 rpm, chatter occurred at a large peak of 507.52 Hz. As the speed was increased to 2100 rpm, the amplitudes corresponding to other frequencies were very small except for the low-frequency band around 300 Hz from the vibration of the machine and the tooth passing frequency and its harmonic frequency. When the hob speed was set at 2400 rpm, the acceleration amplitude came to the maximum at 480 Hz. Besides, a peak appeared at 510 Hz, but the acceleration amplitude was relatively small. At this moment, the workpiece rotation shaft mainly performed forced vibration.

It is worth noting that in Fig. 12a, when the speed was 2100 rpm, there were several frequencies with large amplitude peaks in the frequency range of 440–550 Hz. Unlike the acceleration amplitude which slowly concentrated at 507.52 Hz with a speed of 1800 rpm, the peak frequency here appeared discretely. This phenomenon was regarded as a kind of interference of the experimental results due to uneven workpiece materials or abnormal machine tool during the machining process.

In Fig. 12a–c, the frequency spectrum shows the same change law corresponding to different hob rotation speeds. It is obvious that when the hob rotation speed was 2100 rpm, the result was similar to that in the time domain analysis of the vibration signal. And when $n = 2100$ rpm, $f = 10$ mm/min, and $a_p = 0.5$ mm, the amplitude corresponding to different frequencies was smaller than the other tests, which indicated that chatter performed little negative impact on the machining process in this working condition.

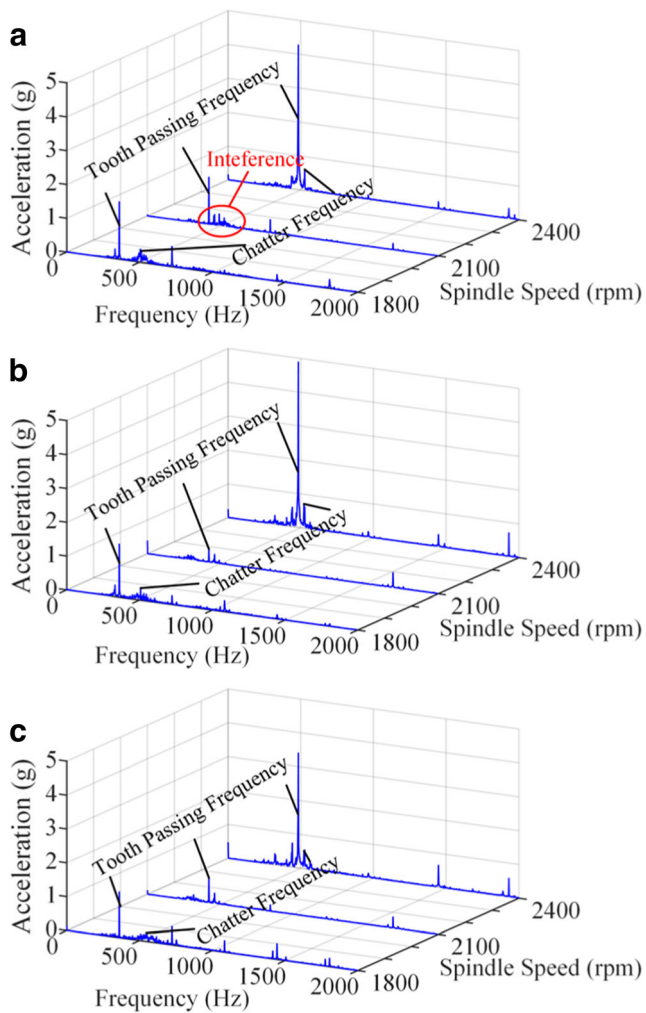


Fig. 12 Acceleration signal spectrum of test 1–9: (a) $f=8$ mm/min, $a_p=0.3$ mm; (b) $f=10$ mm/min, $a_p=0.5$ mm; (c) $f=12$ mm/min, $a_p=0.7$ mm

4.3 Gear measuring results

4.3.1 Geometric precision analysis

Measurement of machined gears was conducted to study the influence of chatter on total tooth profile deviation (Fig. 13). The tooth profile total deviation was detected by the gear measurement center JE32 (produced by Harbin Jingda Measuring Instruments Co., Ltd., China). Gears produced by hobbing in this experiment are shown in Fig. 14.

For $f=10$ mm/min, $a_p=0.5$ mm, and $f=12$ mm/min, $a_p=0.7$ mm, when the hob rotation speed was 2100 rpm, the gear’s deviation was the smallest. When $f=8$ mm/min and $a_p=0.3$ mm, as described in Section 3.2, when the hob speed was 2100 rpm, other peak frequencies (450–480 Hz) occurred due to uneven materials or environmental interference; therefore, in this test, the deviation was not the minimum.

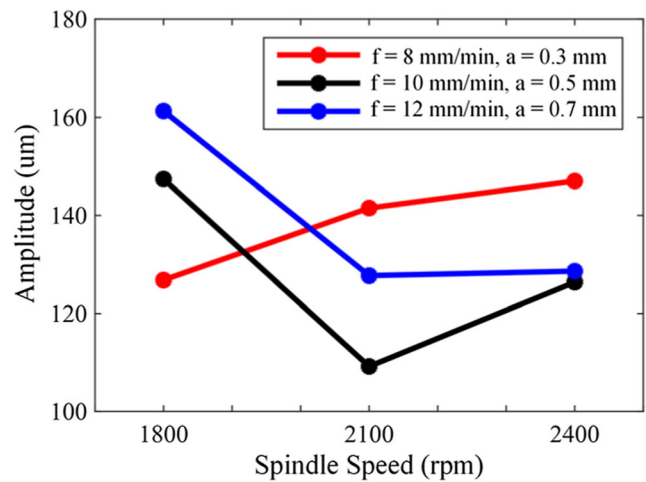


Fig. 13 Tooth profile total deviation of 9 groups of processed gears

4.3.2 Surface topography analysis

When chatter occurs, the increase of the cutting force is followed by an increase of the surface roughness and the deterioration of surface quality [24]. This study mainly studied the process of machining the final surface with the third feed of the hob. Chatter means that the tool vibrates strongly along the Y direction, and teeth will have a strong impact on the surface of the workpiece, which will cause teeth to cut more material. Overcutting and severe scraping of teeth on the machined surface will reduce the surface quality of gears [25–27].

In addition to the detection and analysis of the geometric precision of machined gears, it is necessary to analyze surface topographies. This section studied the influence of chatter

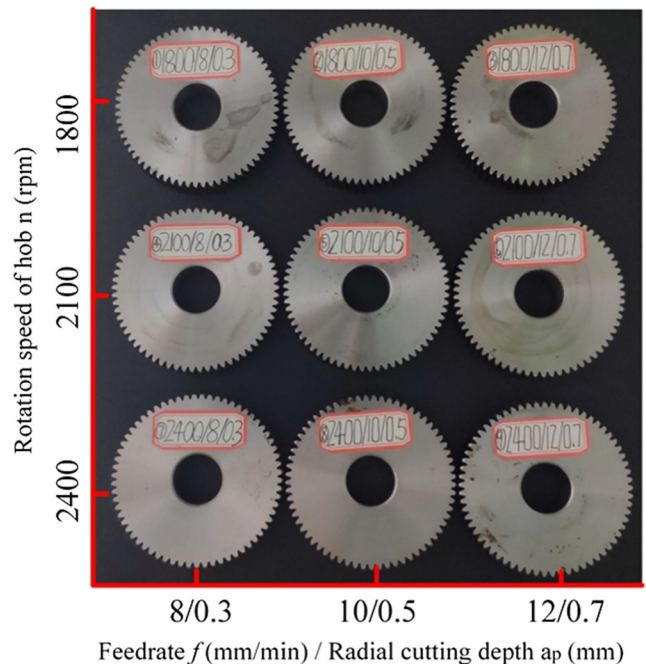
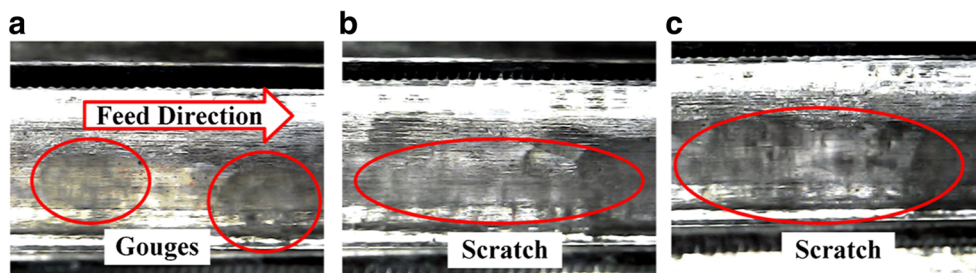


Fig. 14 Processed gears by hobbing

Fig. 15 Surface topographies of machined gears with the same hob speed 1800 rpm and different feedrate and radical cutting depth: (a) $f = 8$ mm/min, $a_p = 0.3$ mm; (b) $f = 10$ mm/min, $a_p = 0.5$ mm; (c) $f = 12$ mm/min, $a_p = 0.7$ mm



caused by the spindle speed on the surface topography of processed gears.

Figures 15, 16, and 17 have shown the surface topographies of processed gears measured by digital microscope Dino-Lite AM2111 (produced by AnMo Electronics Corporation, Taiwan, China). As shown in Fig. 15, when the speed of the hob was 1800 rpm, there were gouges on the gear's surface with the occurrence of chatter according to the above research. When the hob speed came to 2100 rpm, the machine tool was in a stable cutting state. Except for small ridges caused by uneven material of the workpiece and characteristics of hobbing, there were no obvious machining defects. It was the same as that observed at 2400 rpm. The gear surface topographies were similar.

There are two possible reasons for the above processing results:

1. Unstable cutting conditions have a strong effect on the cutting force between the workpiece and the hob, and chatter will produce an excessive cutting effect on the surface of the workpiece. Because of the existence of chatter, many gouges and scratches are left on the gear's surface.
2. Forced vibration originated from cutting force exists in any machining conditions of hobbing. Although the vibration amplitude and fluctuation value at 2100 rpm were smaller than those at 2400 rpm, forced vibration is inevitable in the former condition that has no intense impacts like chatter which used to leave gouges and scratches on

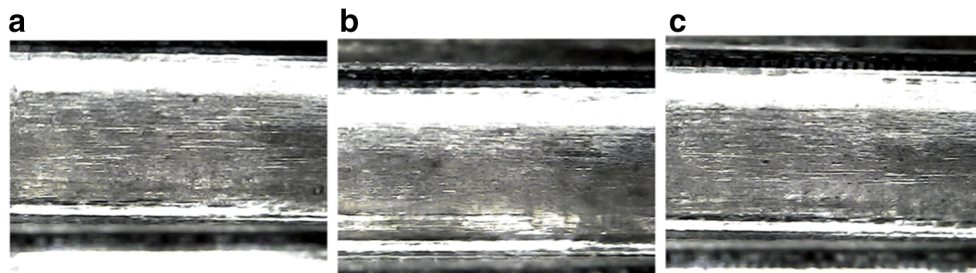
the gear's surface, so forced vibration will not produce processing defects that affect the surface topography.

5 Conclusions

This paper studied the detection and visualization method of chatter on the CNC hobbing machine, the relationship between the hob rotation speeds, and the natural frequency of the workpiece rotation shaft, and the vibration in the hobbing process was analyzed. The optimal hob speed that stabilized the cutting process was predicted previously before the cutting experiment, and the gear cutting experiment was conducted to record acceleration data during processing. By analyzing the acceleration data in time and frequency domain, we could obtain the optimal cutting parameters of the machine tool, achieve the purpose of vibration suppression of hobbing machine tools, and improve the processing precision of gears. Finally, the gear measurement center was used to measure the 9 sets of machined gears to obtain the total tooth profile deviation of gears, and the formation of gouges and scratch was analyzed.

Through the whole experimental and theoretical research, it is found that the vibration during the hobbing process is not linear with the hob rotation speed. When the hob tooth passing frequency is close to the natural frequency of the workpiece rotation shaft, the workpiece

Fig. 16 Surface topographies of machined gears with the same hob speed 2100 rpm and different feedrate and radical cutting depth: (a) $f = 8$ mm/min, $a_p = 0.3$ mm; (b) $f = 10$ mm/min, $a_p = 0.5$ mm; (c) $f = 12$ mm/min, $a_p = 0.7$ mm



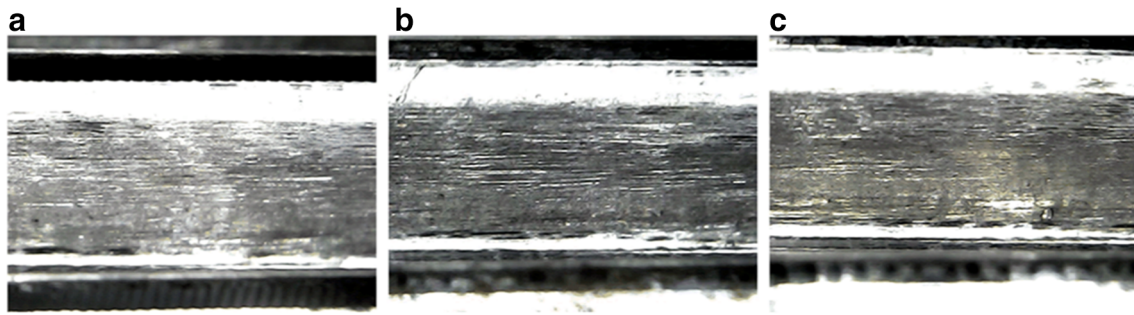


Fig. 17 Surface topographies of machined gears with the same hob speed 2400 rpm and different feedrate and radial cutting depth: (a) $f = 8$ mm/min, $a_p = 0.3$ mm; (b) $f = 10$ mm/min, $a_p = 0.5$ mm; (c) $f = 12$ mm/min, $a_p = 0.7$ mm

shaft vibration and the acceleration fluctuation will be small with a better total tooth profile precision and surface topography. On the other hand, through the analysis of the time and frequency domains of the gear machining acceleration data and the analysis of the final gear measurement results, $n = 1800$ rpm, $f = 10$ mm/min, and $a_p = 0.5$ mm are the optimal parameters with smaller vibration, higher total tooth profile precision and surface topography.

The significance of this study lies in using a combination of time and frequency domain analysis of gear processing acceleration data to detect and visualize the chatter phenomenon during machining, which can be applied to monitor the real-time state of the machine and modify cutting parameters for hobbing as an in-process strategy for chatter recognition. On the other hand, this method is also meaningful for the structure design of machine tools; it is of great significance to adjust the machine's natural frequency and improve the dynamic performance during the design and testing period.

This study adopted the method of combining experimental and theoretical analysis to achieve the detection and visualization of chatter phenomenon from the perspective of time domain and frequency domain analysis. Through machining gear deviation detection and machining surface observation, we hope to study the influence of vibration on gear surface quality. In this study, vibration along the Y direction was mainly considered. Otherwise, in the practical process, the flexible modes of the workpiece and the tool may not necessarily be associated with the same principal directions; besides the tool-workpiece system can have coupled inertial, stiffness, and damping matrices [28, 29]. The in-depth study on low depths of cuts with flexible workpieces in long-term research will be conducted. Furthermore, the method of chatter detection and visualization is considered to be embedded in the operation system of CNC gear hobbing to achieve online chatter suppression.

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