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ORIGINAL ARTICLE

Tool condition monitoring based on dynamic sensitivity of a tool-workpiece system

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Abstract
This paper studies the dynamic sensitivity-based tool condition monitoring and finds the factors that affect tool wear under operation. First, the dynamic sensitivity of the method is discussed in the article. This discussion is divided into three parts: (i) The hammer test on the computer numerically controlled (CNC) lathe is carried out to study the sensitive components and sensitive directions of low-frequency modes in the static state. (ii) The modal parameters of tools are identified by using the method of operational modal analysis (OMA) in the cutting process. The sensitivities of the operational modes and different directions are analyzed, with a description of the variation of the tool-workpiece system. (iii) Sensitive directions and dominant modes that affect tool wear are obtained by comparing and analyzing the dynamic sensitivity under static and operational states. Furthermore, the results of tool condition monitoring experiments are analyzed and discussed. The characteristics of the tool wear state are obtained based on dynamic sensitivity under different cutting parameters. Additionally, machining applications based on dynamic sensitivity are discussed in three aspects: tool wear rate, process design optimization, and cutting depth optimization. Finally, the results show that the method can be used to characterize the wear state of the tool. A reliable method of tool state monitoring that is independent of the cutting speed has been found.

Keywords Operational modal analysis · Dynamic sensitivity · Tool wear · Process optimization

1 Introduction

Tool condition monitoring is very important for process automation because the excessive wear of the tool can cause distortion of the machining dimension, sometimes increasing the scrap rate and the production cost [1]. Tool condition monitoring is very important for reducing the tool wear rate, workpiece surface quality control, and process optimization. At present, tool wear monitoring methods are divided into two basic methods: the direct monitoring method and the indirect monitoring method. Most of the monitoring methods are indirect [2–7].

The direct monitoring method such as the analysis of tool states by obtaining visual or optical signals is difficult to use in actual processing because the tool and workpiece are always in contact in the actual process, and sometimes a chip will be attached to the cutting edge. Moreover, the cutting fluid takes away a large amount of heat produced by cutting to improve the cutting process conditions. Thus, the direct method is more difficult to apply [8].

Most monitoring signals used in the indirect monitoring method are acoustic emission (AE), cutting force, and vibration acceleration signal. AE is dependent on the structure of the cutting material rather than the cutting tool. The AE signal is used to obtain higher frequency bands due to material plastic deformation. The most serious limitation of AE methods is the analytical technique, not the sensing technique [9]. The correlation between cutting force and tool wear has been widely recognized [10]. However, it is difficult to monitor the tool status with the cutting force signal in the actual machining condition. For example, the volume of a dynamometer is relatively large, which will cause great problems for actual processing. The machining vibration is caused by the periodic change of the cutting force dynamic component. Vibration takes place on the tool in the cutting process [11]. Vibration signals have some advantages such as robustness,

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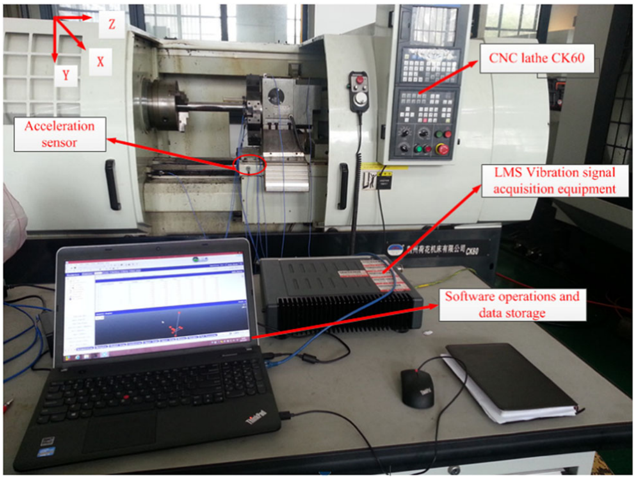

Fig. 1 Experimental setup

reliability, and fast response, which are important for real-time online monitoring. Furthermore, the accelerometer is easily installed and does not affect the cutting process.

Vibration signals are used to monitor tool status in many research studies. Four kinds of signal are characteristic of tool wear: the natural frequency amplitude, the high-frequency band amplitude, the tooth frequency, and the frequency band energy.

Lim GH [12] found that there is a strong correlation between tool wear and the amplitude of the frequency of the tool bar. When the vibration amplitude reaches the second peak, the tool is rapidly reaching its wear limit. Dimla Sr DE et al. [1] analyzed the correlation between tool dominant frequency amplitude and tool wear. Aghdam BH et al. [13] analyzed the correlation between the main modal change of the tool bar and tool wear.

Chelladurai H et al. [14] analyzed the correlation between tool high-frequency band amplitude and tool wear. González LA et al. [15], Rao KV et al. [16], and Babu GP et al. [17] analyzed the correlation between the maximum amplitude in the high-frequency band and the tool wear, and the frequency shift occurred at the severe stage of tool wear. Bhuiyan MSH et al. [18] analyzed the correlation between tool height root mean square (RMS) amplitude and tool wear.

Orhan S et al. [19] analyzed the correlation between the first three orders of harmonic amplitudes and the tool wear. Kalvoda T et al. [20] analyzed the correlation between PSD energy change of tool tooth frequency and tool wear. Sevilla CPY et al. [21] found that the dominant frequency will be derived between the tooth frequency and the first harmonic frequency when the tool wear reaches the failure point.

Stavropoulos P et al. [22] studied the correlation between the average energy of the high-frequency band and the tool wear in the vibration of the workpiece. Rmili W et al. [23] studied the normalized average energy of the high-frequency band and tool wear in the vibration of the tool bare terminal end.

The existing research progress is illustrated from three aspects: frequency domain analysis method, analysis frequency, and arrangement of measurement points. For frequency domain analysis, spectrum analysis is usually carried out directly. For the analysis frequency, the natural frequency of the tool bar is usually studied in the high-frequency areas, and the value of the root mean square or the maximum amplitude is usually selected. The frequency and harmonic frequency of the tool or spindle are generally studied in the low-frequency areas. The measuring points are usually arranged on the tool, the spindle or the workpiece in the milling process. The research of tool condition monitoring aims to find a tool wear identification method that is independent of cutting parameters.

Dimla Sr DE et al. [1] found that the tool life can be identified by the tool nose wear, which is better than the side tool. Therefore, this paper focuses on the correlation between tool wear and the vibration signal of turning tools. In the cutting process, the change of tool and workpiece system will lead to the change of the low-frequency operation mode of the NC machine tool structure. The low-frequency operational mode of the NC machine tool will change with the position of the tool and the workpiece system during the cutting process. In this paper, the tool nose wear will be studied based on the OMA in the NC turning process.

The dynamic change of cutting tool and workpiece system is studied based on OMA. Second, the PSD signal of vibrational response is processed by the Op.PolyMax algorithm. The operational modes of NC machine tools can be

Table 1 Experimental system parameters

Components	Parameters
Machine tools	CNC lathe K60 with the CNC system of HNC-818A
Data collection system	LMS vibration signal data acquisition (model: SCM05)
Data analysis software	LMS Vibration signal data processing (model: Test. Lab 10)
Cutting tool	Mitsubishi turning tool (model: PTGNR2525M16)
Workpiece	45 steel, 40 Cr
Vibration response sensors	Model: PCB-356A15

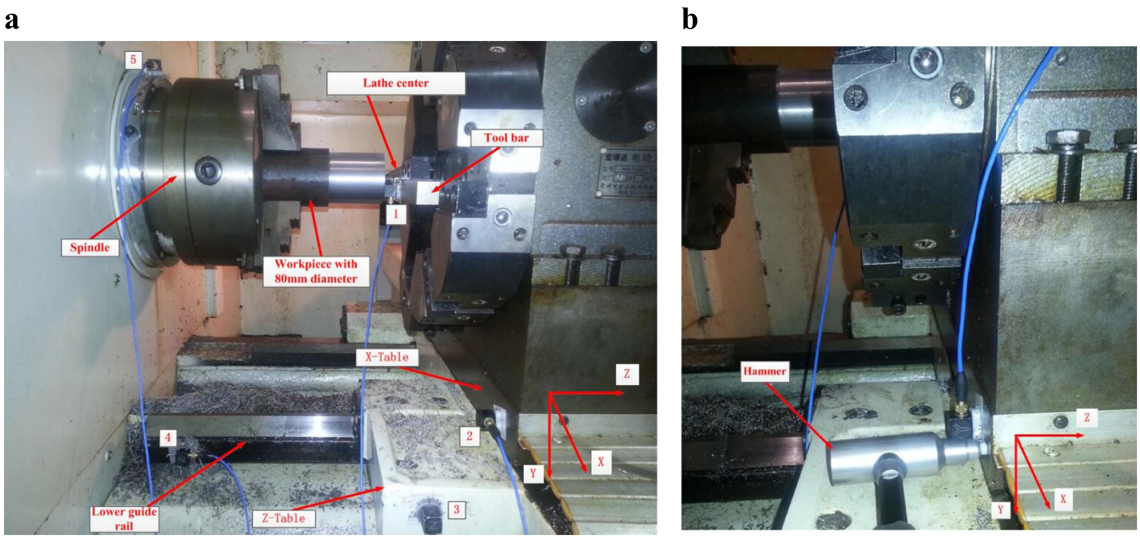

Fig. 2 Experimental setup. **a** Accelerometer mounting. **b** Hammer setup

identified more accurately. The operating modes of different parts are analyzed in the low-frequency range, and the sensitivity of the tool workpiece system is analyzed in different directions, which are defined as a dynamic sensitivity method.

Tool condition is monitored by the dynamic sensitivity method in this paper, and the correlation between the operational modes and the tool wear is analyzed. In addition, three processing applications are mentioned: tool wear rate, process design optimization, and cutting depth optimization. This paper is organized as follows: Section 2 discusses the dynamic sensitivity of the method. This part is divided into three parts as follows. (i) The hammer test on the CNC lathe is carried out to study the sensitive components and sensitive directions of low-frequency modes in static state. (ii) The modal parameters of tools are identified by using the method of OMA in the cutting process. The sensitivities of the operational modes and different directions are analyzed, describing the variation of the tool-workpiece system, and (iii) sensitive directions and dominant modes that affect tool wear are obtained by comparing and analyzing the dynamic sensitivity under static and operational states. Section 3 presents the results of tool condition monitoring experiments that are analyzed and discussed. The characteristics of tool wear state are obtained based on dynamic sensitivity under different cutting parameters. Section 4 presents the machining applications based on dynamic sensitivity discussed in three aspects: tool wear rate, process design optimization, and cutting depth optimization. The work is summarized, and future work is presented in the conclusions.

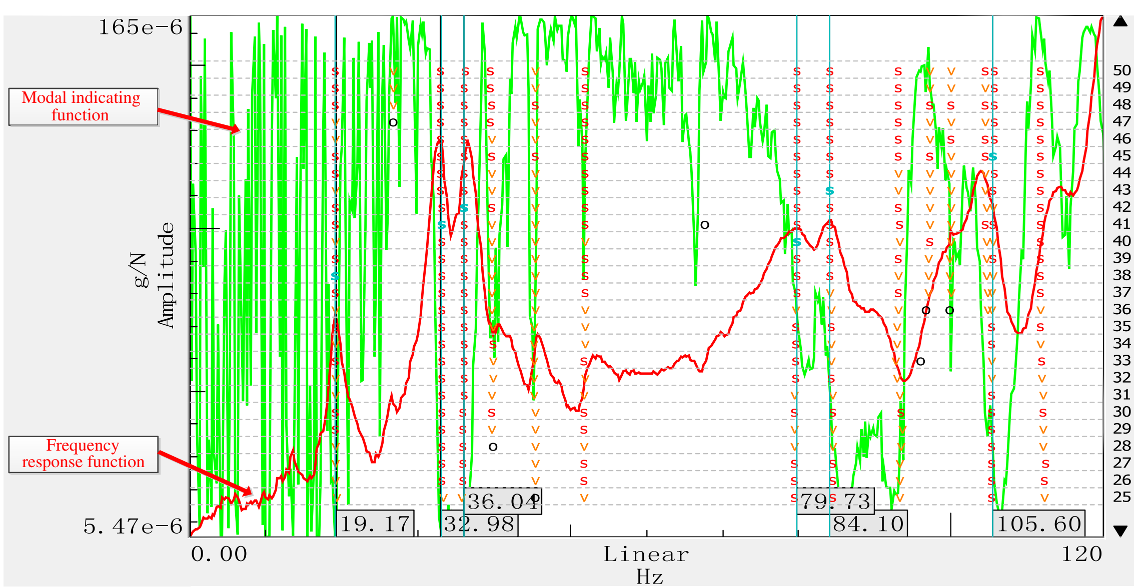

Fig. 3 Mode stabilization diagram using Op. PolyMAX

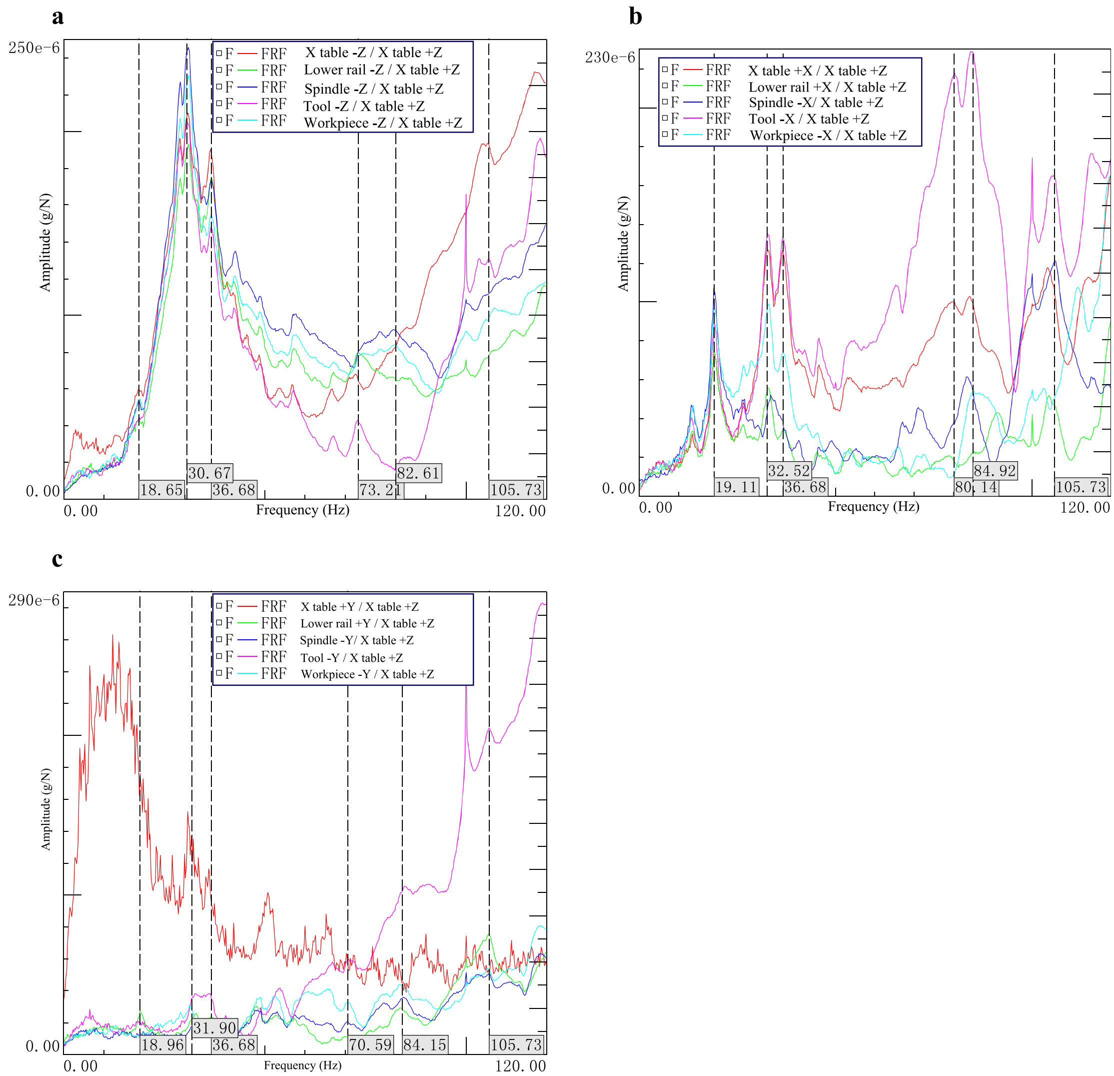

Fig. 4 FRF of the measuring points with impact in the z-direction of the x-table

2 Dynamic sensitivity methods

2.1 Experimental setup

Figure 1 presents an experimental system for hammering and cutting.

Table 2 Modes and sensitivity in 0–120 Hz frequency band of the CNC lathe

Modes	Natural frequency (Hz)	Damping ratio (%)	Sensitive direction	Sensitive components
1st	19.045	1.49	X	Spindle
2nd	30.769	1.14	Z	Spindle
3rd	36.218	0.99	Z	Spindle
4th	77.391	1.85	–	–
5th	85.550	3.85	X	Tool
6th	89.579	0.39	X	Tool
7th	105.149	0.41	X	Spindle

The details of the experimental system are shown in Table 1, below.

Figure 2a presents the cutting process system and the sensor points arrangement. The details are as follows: Point 1 is on the cutter bar, point 2 is on the X-worktable, point 3 is on the Z-worktable, point 4 is on the lower rail, and point 5 is on the spindle.

2.2 Dynamic sensitivity analysis under static state

2.2.1 Hammer setup and modal calculation method

The sensitivity of the low-frequency modes is analyzed in the static hammering experiments. Direction of excitation: tool z-direction, x-workbench z-direction, z-workbench x-, y- and z-direction. The frequency response function (FRF) of five points in each direction is obtained by using the Op.PolyMax algorithm. Then, the static modes of the NC machine tool structure (0–120 Hz) are analyzed.

Table 3 Cutting parameters

Cutting parameter	Value
Cutting length	75 mm
Feed speed	25 mm/min
Cutting time	180 s
Total cutting time	126 min
Cutting volume	800323 mm^3
Cutting diameter	From 65.7 mm to 30.3 mm

Figure 2b presents the hammer test in the z-direction of the x-workbench; the remaining points are similar. Figure 3 presents the mode stabilization diagram of the x-direction of the x-workbench under the motivation of the x-workbench z-direction.

The mode stabilization diagram is obtained by FRF using the operational PolyMAX method (Op. PolyMAX) where the green curve is the frequency response curve after integration. The letters in the figure represent the pole steady state, as follows: the "o" stands for extreme instability. The "f" represents the pole stability in the tolerance range. The "d" represents the pole's damping and the frequency stability within the tolerance range. The "v" represents the pole vector stability in the tolerance range of stability. The "s" represents the frequency, damping, and the vector of the pole stability within the tolerance range. With the change of the order of calculation, the case of relatively stable letters can be considered a mode.

2.2.2 Sensitivity analysis of low-frequency modes under the static state

The sensitivity analysis is conducted mainly from the sensitive direction, the sensitive parts, and the dominated mode. If some mode has always been found in the 0–120 Hz band, and their amplitudes are significant by analyzing the FRF of different measuring points, these modes can be considered sensitive to the direction. Under the same strike, the component with the largest FRF amplitude is considered the modal sensitive part. In addition, the mode with the largest amplitude is considered the dominant mode in a certain direction.

Figure 4a presents the z-direction FRF of each measuring point, which shows that the amplitude of 30 and 36 Hz is very significant in the frequency band, so it is sensitive to the z-direction. In addition, the amplitude of 30 Hz is sensitive to the measuring point of the spindle because of its largest amplitude. The amplitude of 36 Hz on the striking point of the x-workbench is the largest, and the amplitude on the spindle (away from the striking point) is submaximal, so the 36 Hz is sensitive to the spindle.

Figure 4b presents the amplitude of 85 Hz as the most significant in the whole frequency band, so the 85 Hz is sensitive to the radial x-direction. The magnitude of 85 Hz is the maximum at the tool point, and the amplitude is submaximal at the strike point, so this shows that 85 Hz is sensitive to tools.

Fig. 5 Tool wear

Figure 4c presents FRF of each measuring point in the y-direction, and the 105 Hz is relatively obvious, while other peaks are not obvious.

According to Fig. 4, the sensitive direction of 105 Hz is the x-direction because its amplitude is relatively prominent. From the amplitude, the amplitude of tool points at 105 Hz is the largest, so it is sensitive to the tool. The same sensitivity analyses were also performed: the striking points are in the tool bar z-direction and the –x, +y, +z-direction of the z-worktable.

2.2.3 Conclusions of sensitivity analysis under static state

By analyzing the mode stabilization diagram of each direction in the five strike experiments, the results are summarized in Table 2 that is combined with the sensitive components and sensitive directions.

From Table 2, there is a certain regularity in modal sensitivity. From the point of the component, the dominant modes of the spindle in the z-directions and x-directions are 35 and 19 Hz, respectively, while 85 Hz is the dominant mode of the tool in the x-direction. From the point of direction, the dominant modes in the x-direction and z-direction are 85 and 36 Hz, respectively. From the point of the frequency band, the z-direction is the modal sensitive direction of the spindle in the lower bands at 30–40 Hz, the x-direction is the modal sensitive direction of the tool in the higher bands at 80–90 Hz, and the modal sensitive directions of 19 Hz (the lowest mode) and 105 Hz (the highest mode) are in the x-direction of the spindle.

2.3 Dynamic sensitivity under operational state

Two experiments with different cutting conditions were carried out aimed at analyzing the operational mode. In the following two experiments, the cutting depth and feed rate remain the same, and the cutting speed decreases as the diameter of the workpiece decreases.

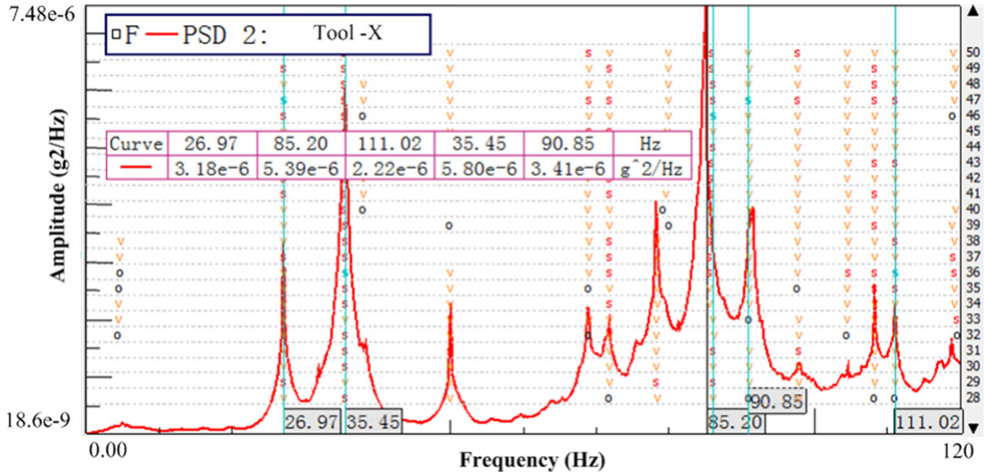

Fig. 6 Mode stabilization diagram of PSD

Test#1. The experiments of turning workpieces (from Φ65.7 mm to Φ30.3 mm) are carried out in the clamping state.

Test#2. The experiments of turning workpieces (from Φ47.3 mm to Φ35.3 mm) are carried out in the cantilever state.

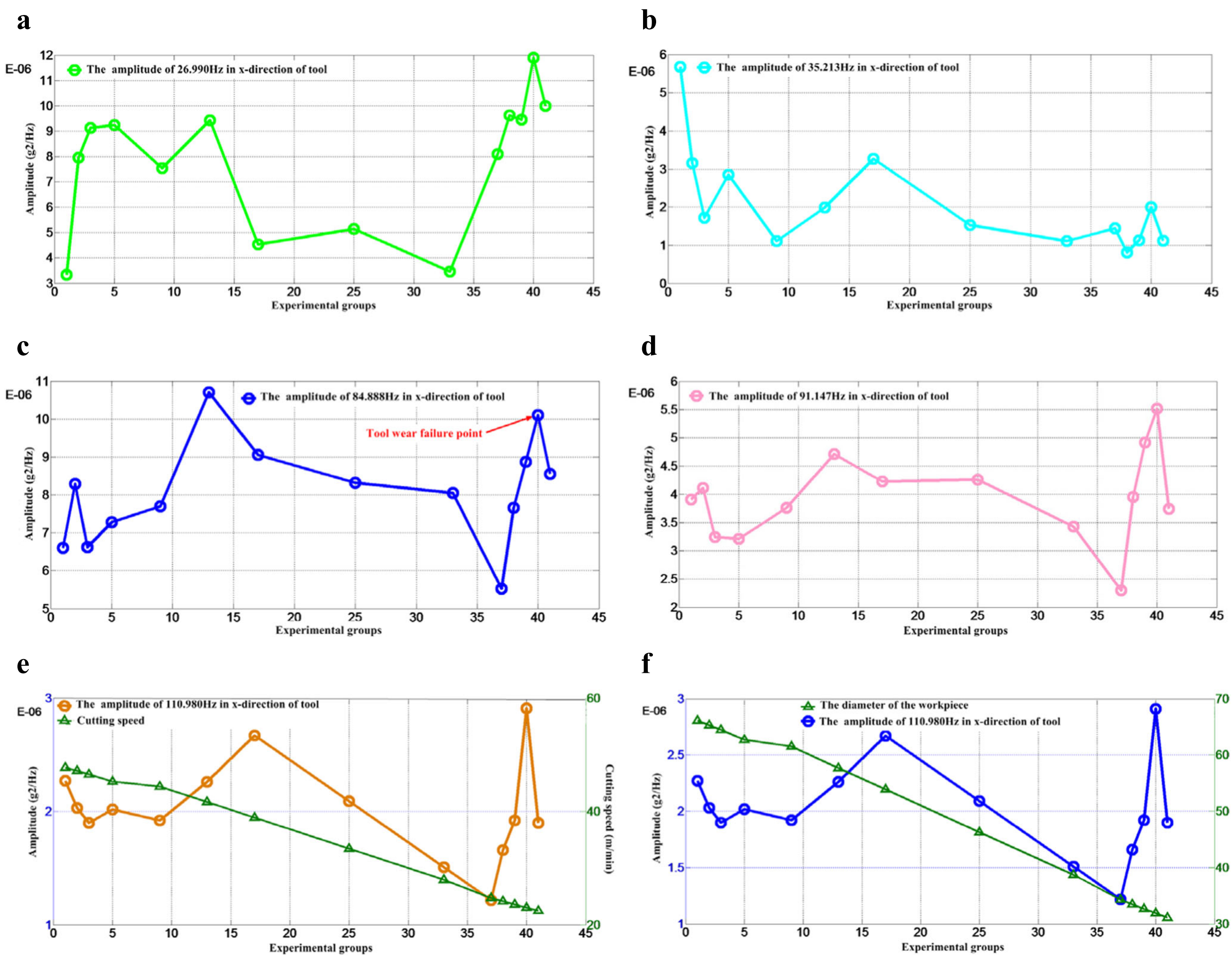

Fig. 7 The magnitude of operational modes in the x-direction. **a** 26.990 Hz. **b** 35.213 Hz. **c** 84.888 Hz. **d** 91.147 Hz. **e** 110.980 Hz with the change of cutting speed. **f** 110.980 Hz with the change of diameter

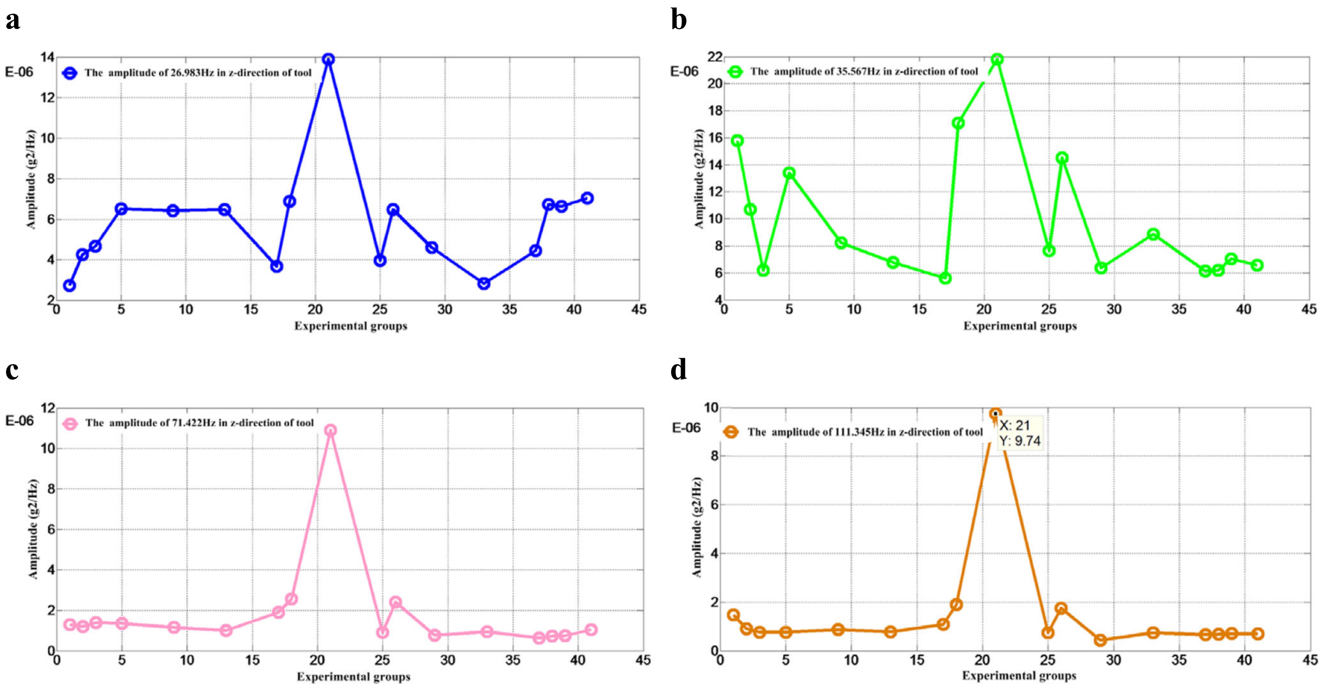

Fig. 8 The magnitude of operational modes in the z-direction. **a** 26.983 Hz. **b** 35.567 Hz. **c** 71.422 Hz. **d** 111.345 Hz

2.3.1 Dynamic sensitivity analysis of the workpiece with 65 mm diameter in the clamping state

The complete tool wear process was divided into 42 groups of cutting experiments, and the cutting parameters are as follows in Table 3.

The cutting parameters remained the same in the 11 groups. The cutting depth is 0.4 mm, the spindle speed is 230 r/min, the cutting time remains constant, and the cutting amount is also approximate. The tool has been worn off after the last groups, as shown in Fig. 5, below.

The power spectral density (PSD) of vibration responses in the x-direction and the z-direction in the 11 groups is analyzed using the Op. PolyMAX. Figure 6 presents the mode stabilization diagram in the x-direction.

Figure 7 presents the magnitude variety of operating modes in the low-frequency range in the x-direction. Figure 7a presents the magnitude of the variation of 26.990 Hz in the x-direction. The operating mode 26.990 Hz corresponds to the natural mode 30 Hz. The wear stage is divided into six stages. Stage 1 (group 1–4): The vibration response amplitude increases as the faster tool tip wears, with the small wear rate and the increasing friction force. Stage 2 (groups 5–12): The tool nose enters the stationary wear stage. The wear quantity is basically the same, and the amplitude is almost the same. Stage 3 (groups 13–16): The amplitude decreases due to the plastic deformation and thermal softening. Stage 4 (groups 17–32): The overall amplitude of vibration response decreases slightly because the workpiece quality decreases greatly, and the tool nose wear increases. Stage 5 (groups 33–39): The amplitude of vibration response increases dramatically because the workpiece quality decreases, the tool wear increases, and the friction force increases rapidly. Stage 6 (group 40–42):

Table 4 Cutting parameters

Cutting parameter	Value
Material	40 Cr
Diameter	50 mm
Cantilever length	120 mm
Cutting depth	0.05 mm
Spindle speed	210 r/min
Cutting length	7 5 mm
Cutting volume	233428 mm^3
Cutting diameter	From 47.3 mm to 35.3 mm

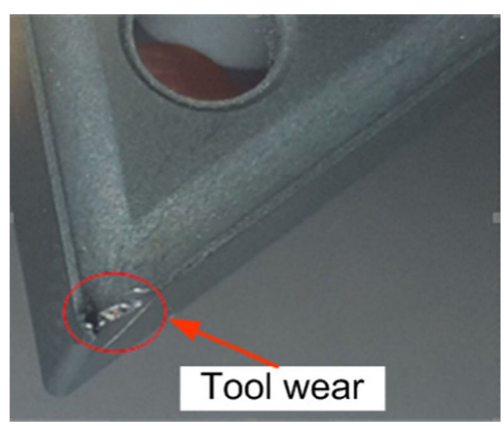

Fig. 9 Tool wear

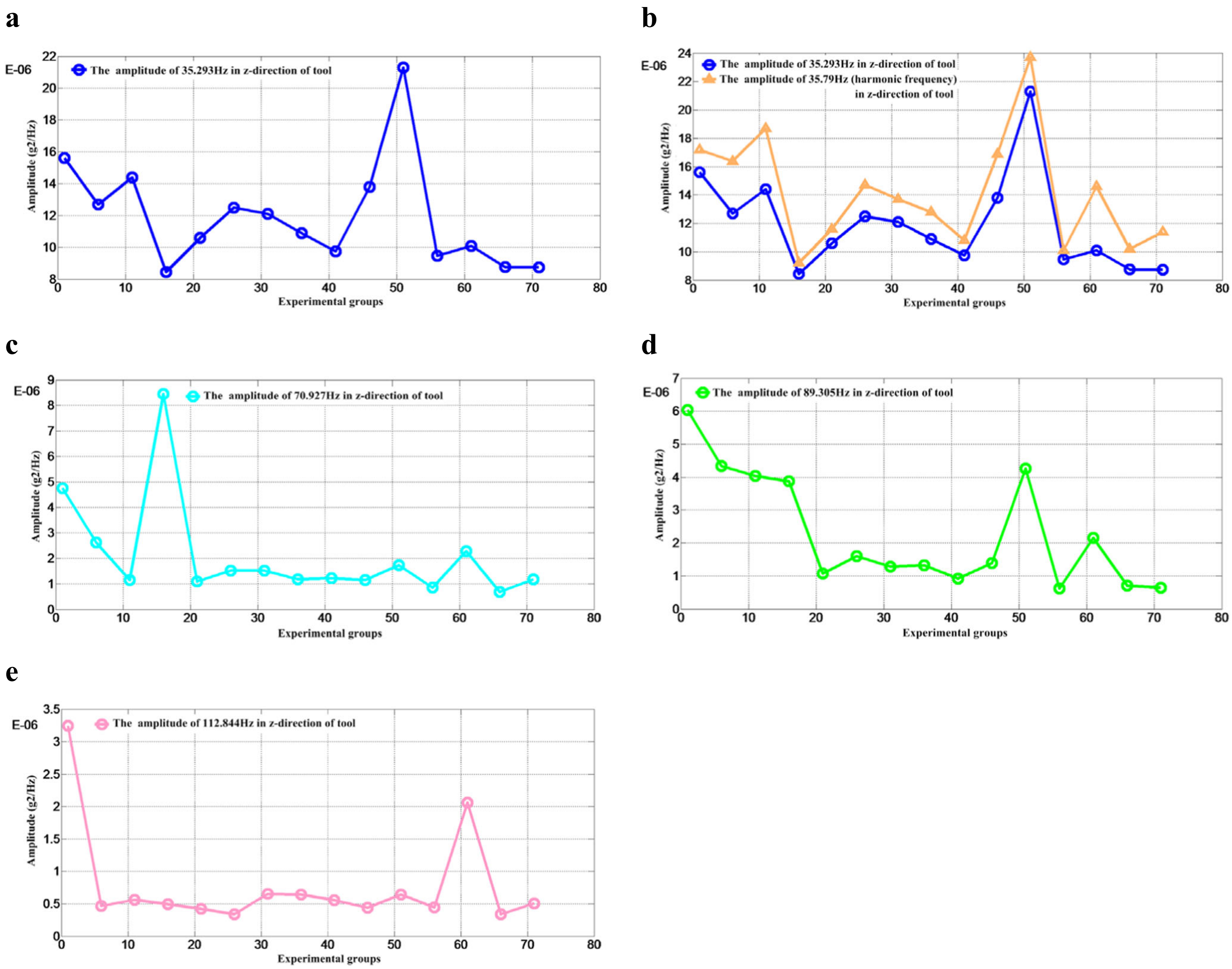

Fig. 10 The magnitude of operational modes in z-direction. **a** 35.293 Hz. **b** 35.79 Hz (harmonic frequency). **c** 70.927 Hz. **d** 89.305 Hz. **e** 112.844 Hz

The amplitude of the vibration response decreases because the friction decreases, and the quality of the workpiece decreases, and the tool front angle increases. Finally, the failure point of tool wear is reached. Overall, the effect of tool wear on the dynamics of the tool and workpiece system is reflected by the variation of the 26.990 Hz amplitude.

Similarly, the following conclusions are obtained by analyzing the variation of the remaining four modes. Figure 7b presents the magnitude variation of 35.213 Hz in the x-direction. The 35.213 Hz is excited by the harmonic frequency 35.79 Hz (the rotation frequency 217 Hz). Periodic excitation mode is more sensitive to workpiece quality and less relevant to tool wear.

Figure 7c presents the magnitude variation of 85 Hz in the x-direction, showing that the energy of 84.888 Hz is larger than the others because of the its largest magnitude. Therefore, 84.888 Hz can be regarded as the dominant mode, which reflects the dynamics of the tool-workpiece system. However, the amplitude variation of the 85 Hz is like the amplitude variation of the tool natural frequency with the cutting time. The 85 Hz is most sensitive to the wear of the tools, but it can still reflect the change of workpiece quality in the steady wear stage.

Figure 7d presents the magnitude variation of 91.147 Hz in the x-direction. The magnitude variation of the 91.147 Hz is like those of 84.888 Hz, but the overall is smaller than the amplitude of the third order. Therefore, the sensitivity of 91.147 Hz is lower than the sensitivity of the 84.888 Hz. The principle of magnitude variation of 91.147 and 84.888 Hz is different from the principle of magnitude variation of the 35.213 Hz, since there are many hard materials in the workpiece, and the pulse excitation is generated during the cutting process.

Figure 7e and f presents the magnitude variation of 110.980 Hz under the turning speed and the diameter of the workpiece, respectively. From Fig. 7e and f, the change of surface quality is more relevant to frequency amplitude than cutting speed in the stable wear stage. There is a small

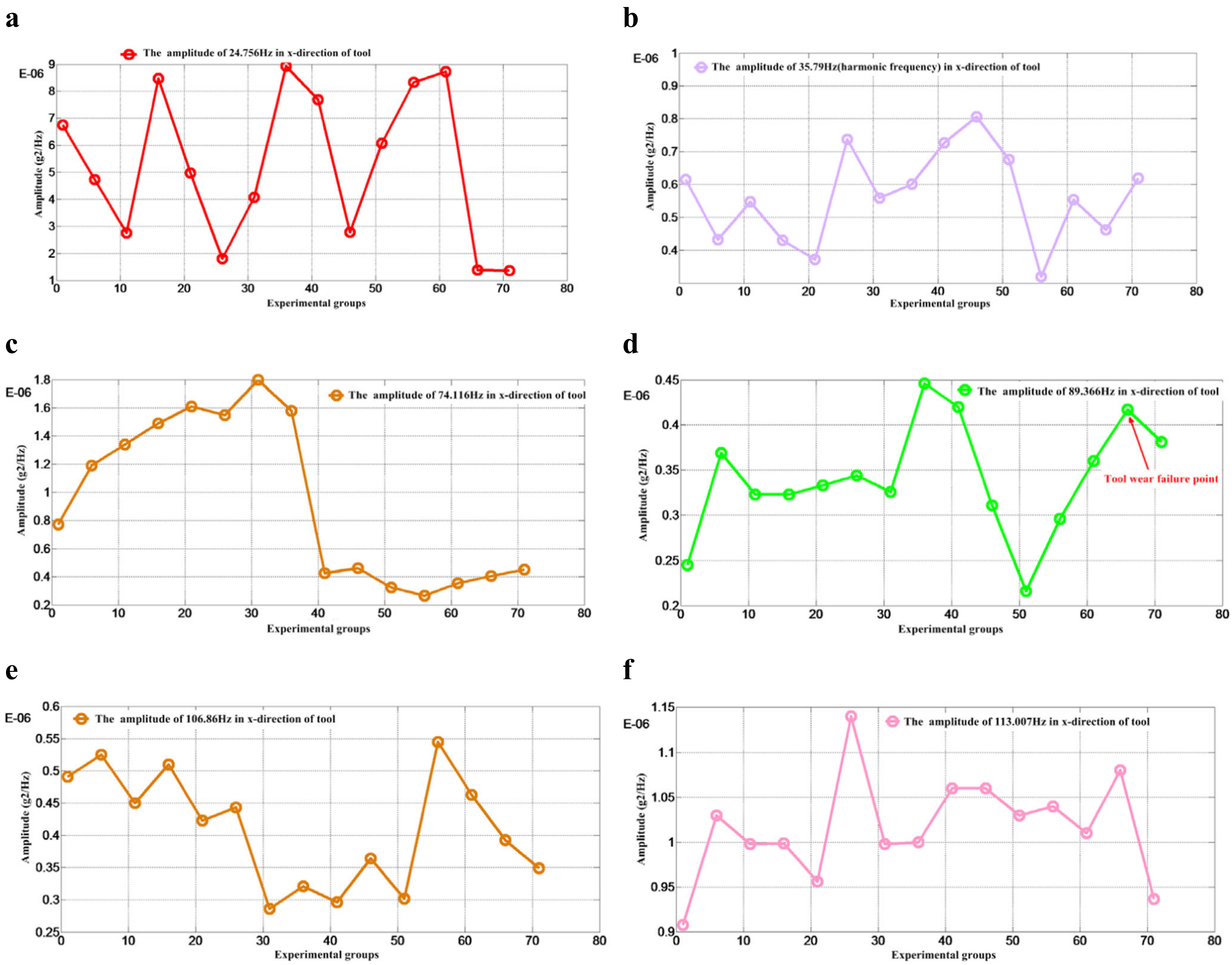

Fig. 11 The magnitude of operational modes in the x-direction. **a** 24.756 Hz. **b** 35.79 Hz (harmonic frequency). **c** 74.116 Hz. **d** 89.366 Hz. **e** 106.86 Hz. **f** 113.007 Hz

deviation in correlation because the wear leads to an increase in the amplitude. Therefore, in the tool workpiece system, the variation of workpiece mass will be considered to analyze the change of frequency amplitude instead of the turning speed.

The magnitude variation of operating modes in the z-direction is analyzed by the same method. Figure 8 shows that the magnitude variation of the z-direction is low sensitivity to the wear of the tool and high sensitivity to the diameter of the workpiece.

Table 5 Cutting parameters of three groups

Parameters	Exp. 1	Exp. 2	
Groups	1st	2nd	3rd
Cutting speed (m/min)	30.3478	19.1059	21.8856
Feed rate (mm/r)	0.0952	0.1786	0.1563
Cutting depth (mm)	0.4	0.05	0.05

2.3.2 Dynamic sensitivity analysis of workpiece with 47 mm diameter in the cantilever state

The complete tool wear process was divided into 71 sets of cutting experiments, and the cutting parameters are as follows in Table 4. The tool has been worn off after the last groups as shown in Fig. 9, below.

Table 6 Cutting parameters in Exp. 1

Cutting parameter	Value
Groups	33
Material	40 Cr
Cantilever length	100 mm
Cutting length	68 mm
Cutting diameter	From 46.8 mm to 28.94 mm
Each group cutting time	2.626 min

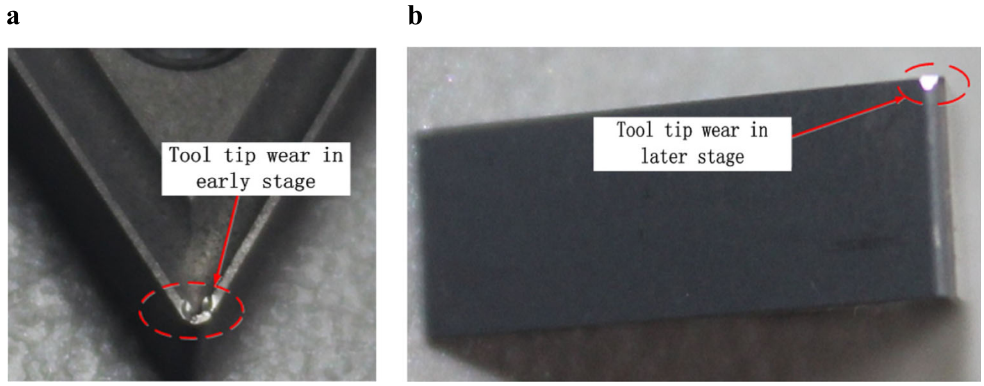

Fig. 12 **a** Tool wear of early stage in Exp. 1. **b** Tool wear of the later stage in Exp. 1

The magnitude of five operational modes in the z-direction is presented in Fig. 10. The lower frequency is less sensitive to the wear of the tool, while the higher frequency is more sensitive to the wear of the tool and the diameter of the workpiece.

The magnitude of the variation of five operating modes in the x-direction is analyzed from Fig. 11, and the following conclusions are obtained: (i) 24.756 Hz is the dominant mode from 0 Hz to 120 Hz, which obviously reflects the three stages of wear, whose amplitude is ten times the other modes. Additionally, 89 Hz is the most sensitive to the wear of the tool. (ii) The plastic deformation and thermal softening effect appear during the large wear of the tool. (iii) The changes of rotating frequency are not related to tool wear which cannot be used in tool condition monitoring.

2.3.3 Conclusions of sensitivity analysis under the operational state

The sensitivity of dynamics is significantly different in direction, component, and frequency.

In the x-direction, the measuring points in the tool better reflect the wear of the tool than the measuring points in the spindle. In the z-direction, the high operational modes are more sensitive to the tool wear and the diameter of workpiece than the low modes.

The mode of resonant frequency and periodic excitation have a low sensitivity to tool wear, while the modes of white noise are the opposite. The cutting speed has little effect on the operational modes; however, the diameter of the workpiece is the opposite.

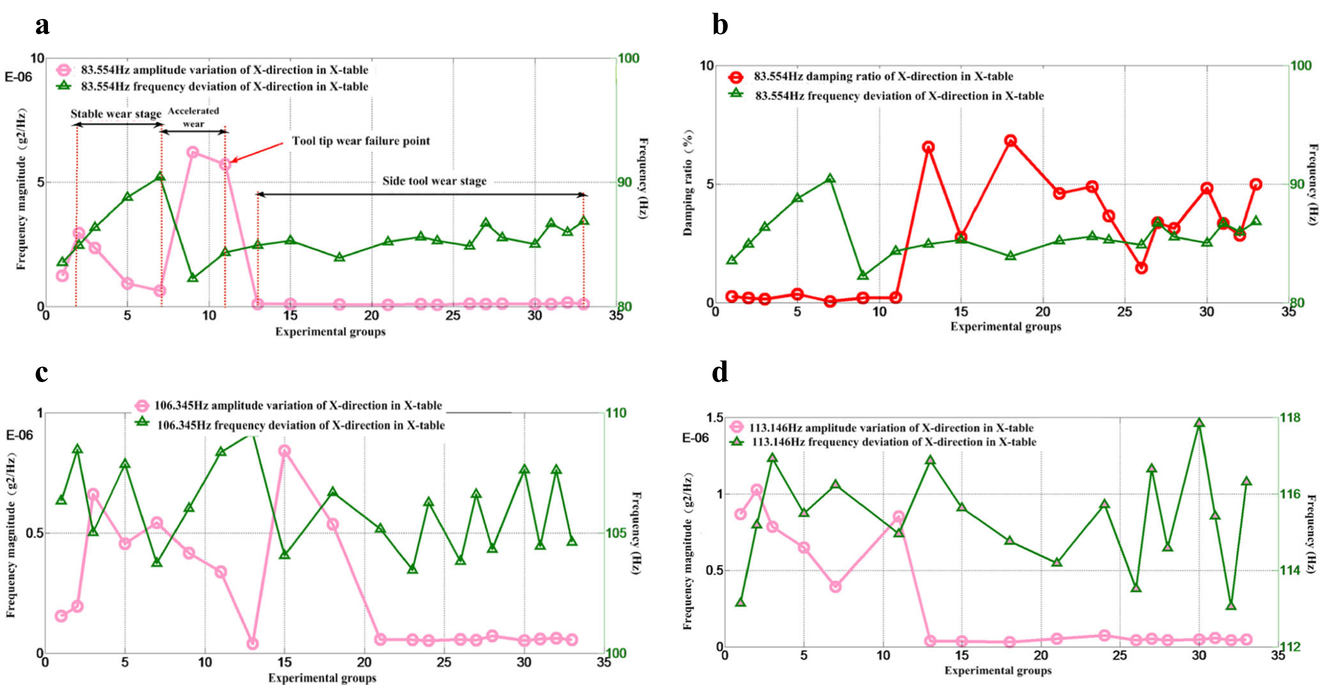

Fig. 13 Operational mode of x-table in the x-direction in Exp. 1. **a** 83.554 Hz with amplitude. **b** 83.554 Hz with damping ratio. **c** 106.345 Hz with amplitude. **d** 113.146 Hz with amplitude

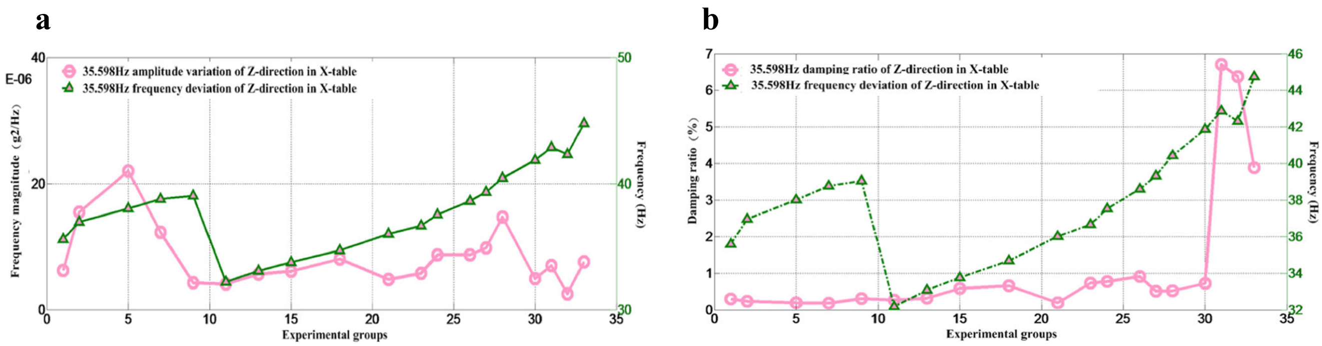

Fig. 14 Operational mode of the x-table in the z-direction in Exp. 1. **a** 35.598 Hz with amplitude. **b** 35.598 Hz with damping ratio

For the dominant modes, the sensitivity between the static modes and the operational modes is high. Although the boundary conditions and other factors change, the sensitive components have not changed, which indicates that the modal sensitivity is the basic property of machine tools. The result shows that the wear of the tool can be reliably reflected by the amplitude of the sensitive operational mode.

2.4 Comparative analysis

In the static state, 85 and 36 Hz are the dominant modes of the x-direction and the z-direction, respectively. The sensitive direction of 36.218 Hz is the z-direction, and the sensitive direction of 85.550 and 89.579 Hz is the x-direction. The sensitive parts are tool and spindle.

In the operational process, 84.888 and 35 Hz are the dominant modes of x-direction and z-direction, respectively. The 85 and 89.579 Hz are the most sensitive to tool wear in the x-direction. The modes of the z-direction (particularly 35.213 Hz) are more sensitive to the diameter of the workpiece and less sensitive to wear.

Some modes, which are identified in static in the range of 0–120 Hz, do not appear in the operational process. There are several Hertz among them, which shows that the static modes identified by impact are different from the actual operational modes.

3 Tool wear monitoring analysis

3.1 Tool wear monitoring under constant cutting parameters

Three different cutting parameters were set up in two cutting experiments. The first groups of parameters were used in Exp. 1. The second and third groups of parameters were carried out in Exp. 2, which were alternated. The tool cantilever length of Exp. 1 and Exp. 2 are 50.39 mm. Three groups of parameters are shown in Table 5, below.

3.1.1 Tool wear identification in Exp. 1

The experimental setup is basically consistent with Section 2.3.1. The cutting parameters are as follows in Table 6.

Figure 12 shows that the tool is worn off after the 33rd group, which indicates that the failure point has been reached.

Figure 13a presents the amplitude variation of the 83.544 Hz that is the sensitive operational mode. The 83.544 Hz amplitude decreases sharply after reaching the wear failure point. Then, its amplitude is reduced approximately 60 times, and the variation is relatively small when the side tool is in the wear stage, showing that the operational modal amplitude is sensitive to the wear of the tip of the tool instead of the wear of the side of the tool. The natural

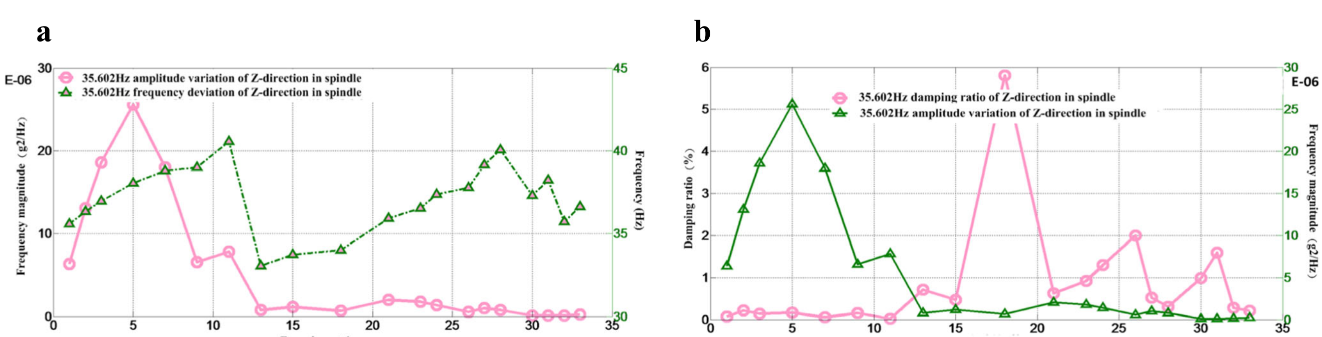

Fig. 15 Operational mode of spindle in z-direction in Exp. 1. **a** 35.602 Hz with amplitude. **b** 35.602 Hz with damping ratio

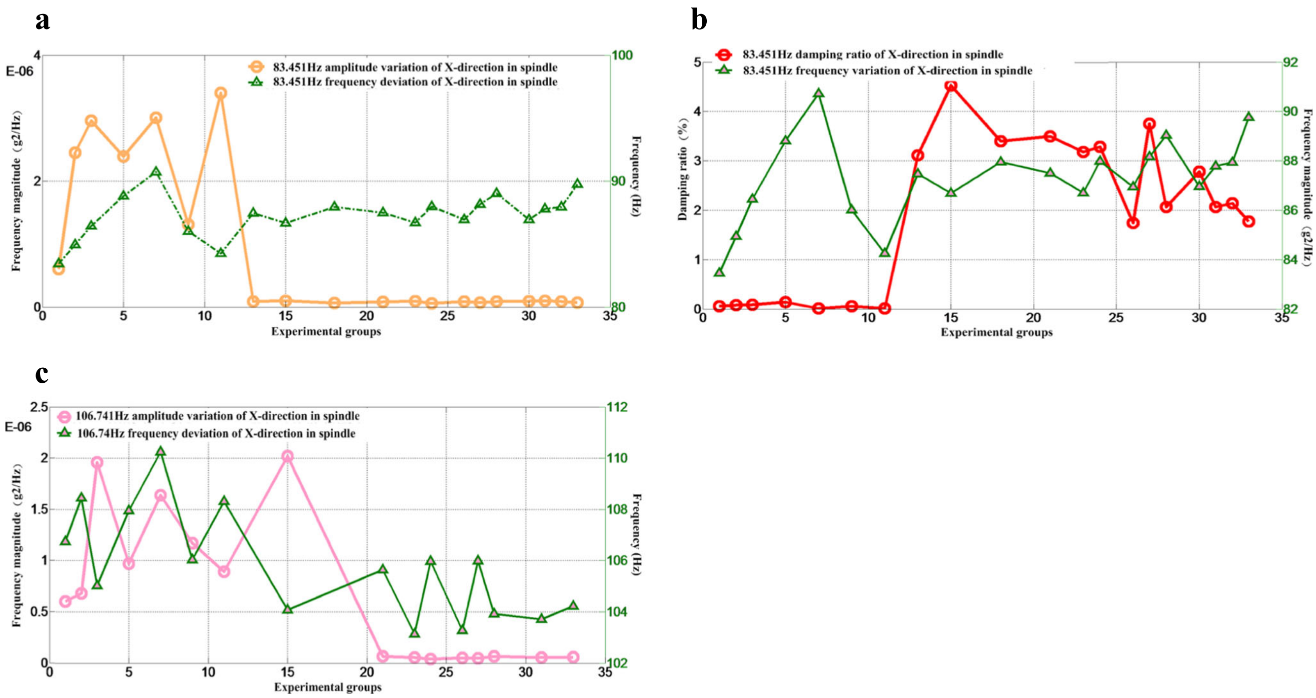

Fig. 16 Operational mode of spindle in x-direction in Exp. 1. **a** 83.451 Hz with amplitude. **b** 83.451 Hz with damping ratio. **c** 106.741 Hz with amplitude

frequency is shifted continuously before reaching the failure point. Then, it is no longer shifted basically and kept at approximately 85 Hz. Therefore, the variation of the tip causes the natural frequency.

Figure 13b presents the variation of the damping ratio at 83.544 Hz. The damping ratio is 24 times the minimum value after 13th group. Then, the damping ratio becomes 5.5 times smaller than the minimum value, showing that the variation of the damping ratio is due to the side tool wear. The variation of the damping ratio in the side tool is like the variation of the amplitude in the tool tip wear. Therefore, the wear of the side tool can be expressed by the variation in the damping ratio.

The 106.345 Hz is not the dominant mode because its energy level is 1/10 of 85 Hz in Fig. 13c. From Fig. 13d, 113.158 Hz corresponds to the 115 Hz mode under stationary conditions, and the variation of the amplitude and the sensitive mode of tool wear are consistent with those of 85 Hz, so the amplitude variation of 113.158 Hz is reliable to characterize the tool wear failure point. From the changes of modes in the 0–120 Hz in the x-direction, the changes of tool wear are reflected by the natural frequency and damping ratio of 85 Hz.

From Fig. 14, the amplitude variation of 35 Hz is not sensitive to the wear of the tool tip, but it is sensitive to the wear of the side tool. The damping ratio of 35 Hz reflects the wear of the side tool. In general, 35 Hz is the dominant mode, which is sensitive to the wear of the side tool in the z-direction.

From Fig. 15, the amplitude of 35 Hz is sensitive to the wear of the tool in the z-direction. However, its damping ratio is sensitive to the wear of the side tool. According to the result of the spindle point and the worktable point in the z-direction from Fig. 14 and Fig. 15, the damping ratio of the spindle is sensitive to the wear of the side tool. In addition, the amplitude of the worktable is sensitive to the wear of the side tool.

Table 7 Cutting parameters in Exp. 2

Cutting parameter	Value
Groups	55
Material	45 steels
Cantilever length	100 mm
Cutting length	65 mm
Cutting diameter	From 43.64 mm to 30.14 mm
Each group cutting time	2.626 min

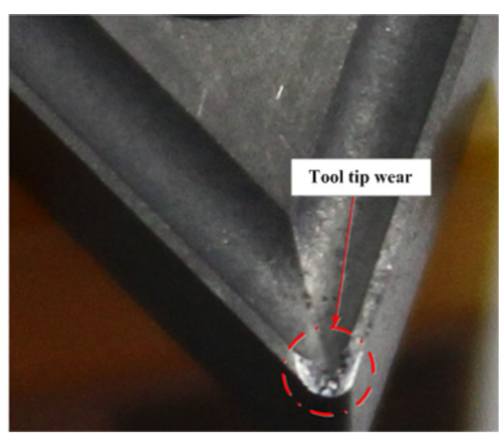

Fig. 17 Tool wear in Exp. 2

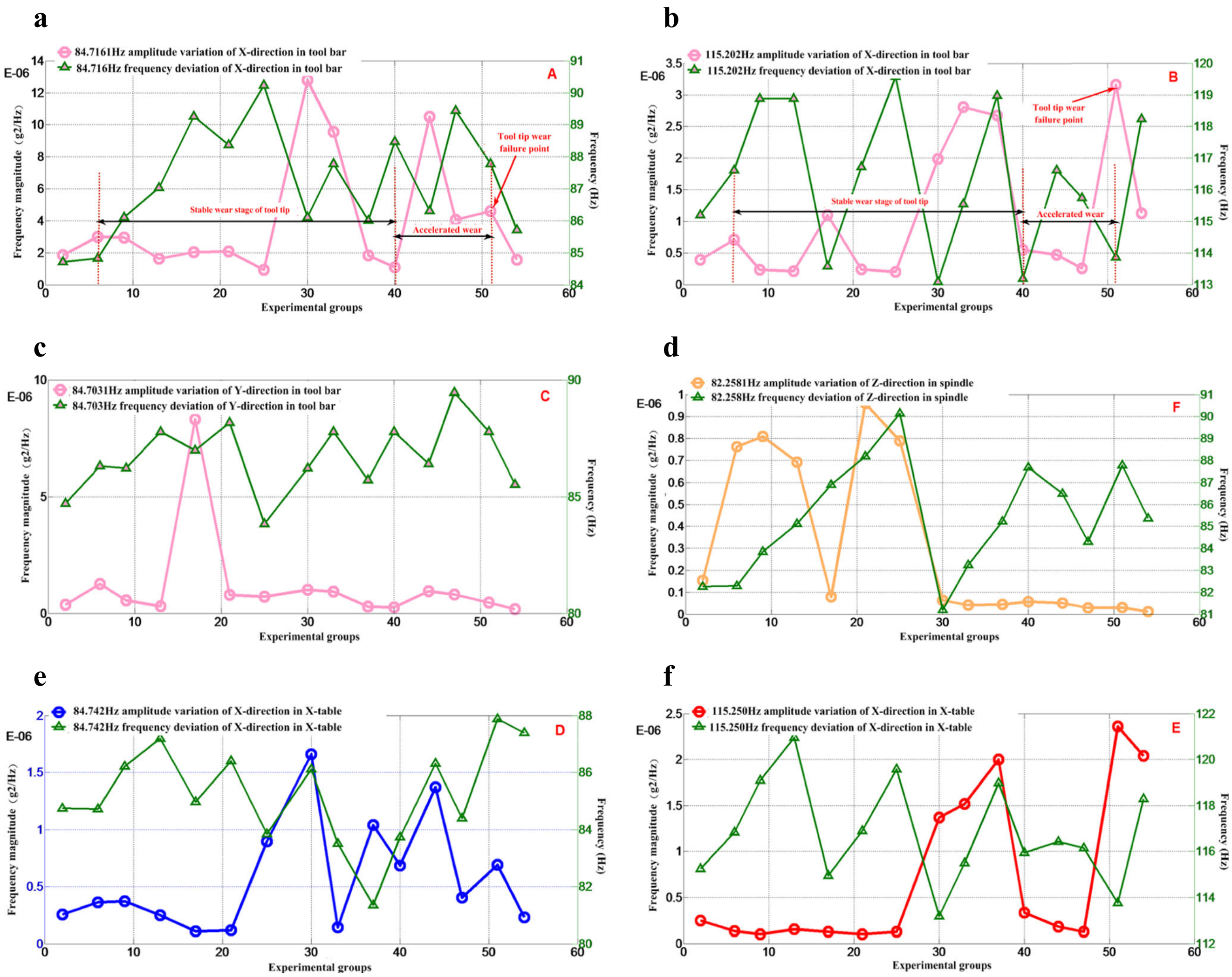

Fig. 18 The modal changes under the second group of parameters. **a** 84.716 Hz in the x-direction of the tool. **b** 115.202 Hz in the x-direction of the tool. **c** 84.703 Hz in the y-direction of the tool. **d** 82.258 Hz in the z-direction of the spindle. **e** 84.742 Hz in the x-direction of the x-table. **f** 115.250 Hz in the x-direction of the x-table

From Fig. 16, the amplitude of 83.451 Hz is sensitive to the wear of the tool. Its damping ratio is small before the tool wear failure point. Then, the damping ratio increases rapidly after the failure point, which shows that it is feasible to characterize the wear of the tool. From Fig. 16c, the amplitude of 106.741 Hz is less sensitive to the wear of the tool, and its natural frequency deviation is irregular.

Conclusion in Exp. 1 According to the analysis of the modal amplitude and damping ratio, the damping ratio of the dominant modes in the x- and z-directions is related to the wear of the tool. The damping ratio variation in the x-direction (85 Hz) and the z-direction (35 Hz) is related to the wear of the side tool. The conclusion is below. (i) When the variation of the damping ratio (35 Hz) is used to characterize the wear of the side tool, the measuring points of the spindle can reflect the early stage of wear, and the measuring point of the worktable is sensitive to the later stage of wear. (ii) When the variation of the damping ratio (85 Hz) is used to characterize the wear of the side tool, the worktable is more sensitive to the early stage of wear than the spindle.

3.1.2 Tool wear identification in Exp. 2

The experimental setup is basically consistent with Section 2.3.1. The cutting parameters follow in Table 7. The cutting parameters of the second and third groups are in the same workpiece, which is alternated.

The tool wear after cutting is shown in Fig. 17. The tool wear is smaller than Exp. 1, not reaching the point of failure.

(i) Under second group of cutting parameters

Figure 18 presents the modal amplitude variations under the second parameters. The x-direction of the x-table and tool

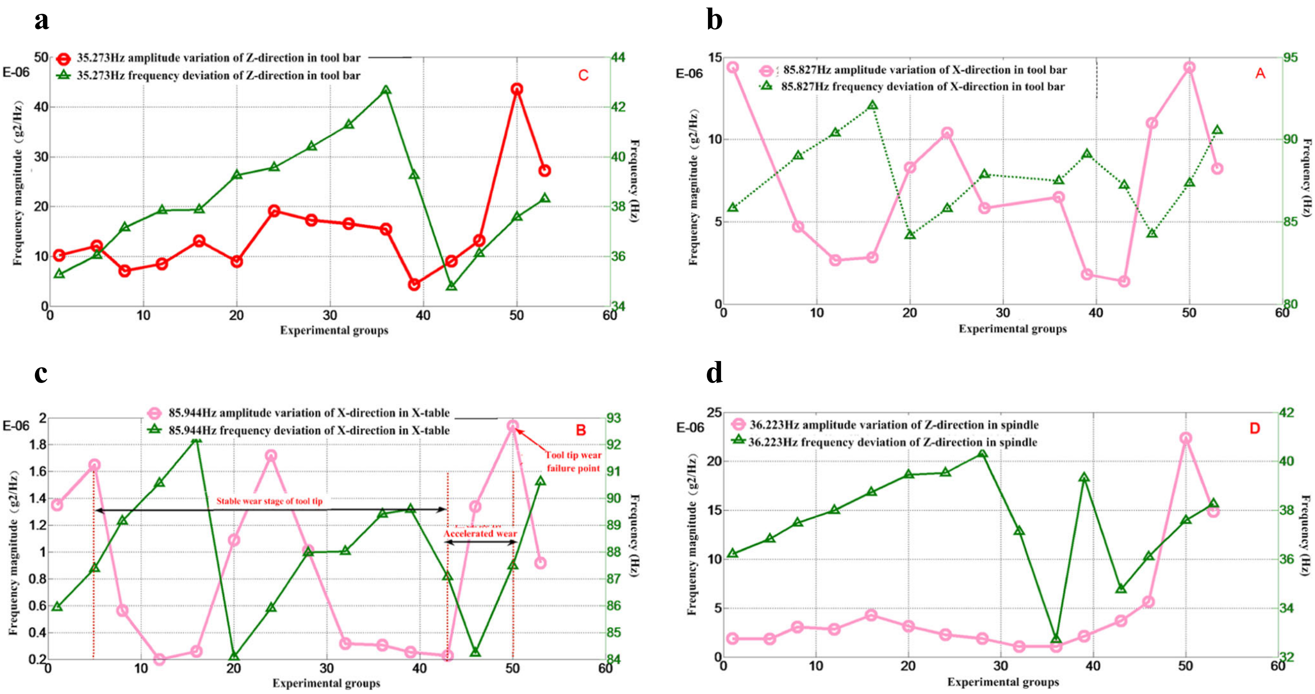

Fig. 19 The modal changes under the third group of parameters. **a** 3 5.273 Hz in the z-direction of the tool. **b** 85.827 Hz in the x-direction of the tool. **c** 85.944 Hz in the x-direction of the x-table. **d** 36.223 Hz in the z-direction of the spindle

is sensitive to the wear of the tool tip, especially the 85 and 115 Hz. The wear of the tool tip can be described by the variation amplitude of 85 Hz. The severe wear of the tool tip is more significant. The spindle is sensitive to the wear of the tool tip at the early stage, but less sensitive at the later stage in the z-direction.

(ii) Under third group of cutting parameters

Figure 19 presents the modal amplitude variations under the third parameters. The x-direction of the x-table and tool bar are sensitive to the wear of the tool tip, especially the 85 Hz. However, the z-direction of the tool bar and the spindle are less sensitive to the wear of the tool tip.

Conclusions in Exp. 2 The modes are excited significantly under the two parameters. The excited mode decreases gradually as the feed rate decreases. The characteristics of the tool tip wear are described by the sensitive mode. From the point of direction, the radial x-direction is more sensitive to tool tip wear, and the feed z-direction is sensitive to a certain mode, while the y-direction is less sensitive to tool tip wear. From the measuring point, the wear of the tool tip is well described by the sensitive modal 85 Hz of the tool bar, x-worktable and spindle.

In general, although the cutting parameters change, mode 85 Hz is still highly sensitive to the wear of the tool tip in the x-direction, and wear points are also consistent, illustrating that the cutting parameters cannot change the reliability of the tool tip wear described by the operational modes.

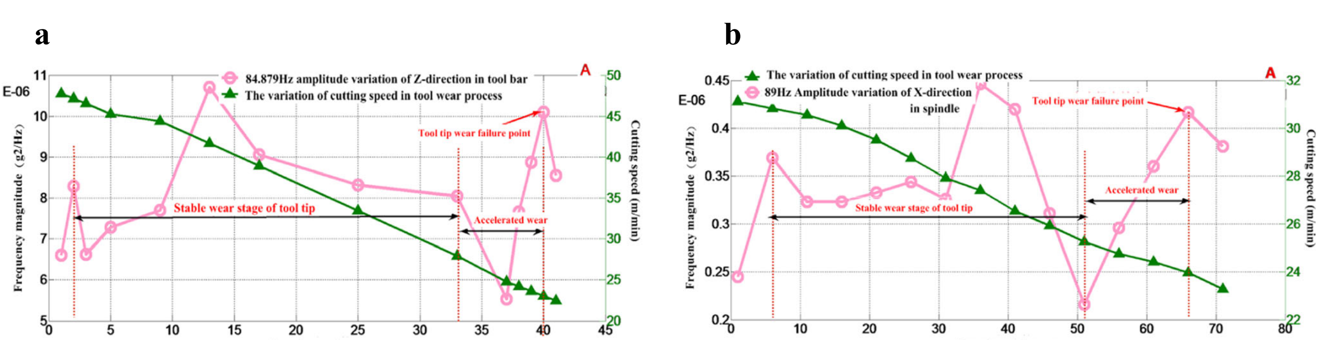

Fig. 20 Changes of sensitive operational modes. **a** The workpiece with 65 mm diameter. **b** The workpiece with 47 mm diameter

Table 8 The first and second cutting parameters

Cutting parameters	1st	2nd
Cutting speed (v_1, v_{23})	30.3478 m/min	20.4958 m/min
Average feed speed (f_1, f_{23})	0.0952 mm/r	0.1675 mm/r
Cutting depth (a_1, a_{23})	0.4 mm	0.05 mm
Cutting speed ratio (v_1/v_{23})	1.48	1.48
Average feed speed ratio (f_1/f_{23})	0.57	0.57
Cutting depth ratio (a_1/a_{23})	8	8

3.2 Tool wear monitoring under varying cutting parameters

In this section, tool wear is identified by two sets of experimental data in (Section 2.3) under varying cutting speeds in Fig. 20.

Under the variation of the cutting parameters, the amplitude of the sensitive operational mode can still characterize the tip wear, showing that the cutting speed has little effect on the modal peak amplitude. The natural frequency is not offset with the cutting speed decreases. The natural frequency offset is due to the tip of the wear, but the reduction of the cutting speed suppresses the increase of the natural frequency. Therefore, the identification method of tip wear, which is independent of the cutting parameters, is characterized by the amplitude of the sensitive operational mode.

3.3 Comparative analysis

There are some similarities and some differences in the analysis of tool wear monitoring by four cutting experiments under variable and constant cutting parameters.

(i) The same points

This section will be discussed by cutting direction, measuring parts, frequency. From the aspect of cutting direction, tool tip wear is highly sensitive to radial x. The z-direction has a good sensitivity to some wear stage. The y-direction of the main cutting is the least sensitive to tip wear. From the aspect of the measuring parts, the 85 Hz of the x-table and the 85 and 89 Hz of the spindle are the most sensitive to the tool tip wear. The x-table is more obvious at the amplitude of 85 Hz, and the spindle is more obvious at the damping ratio of 85 Hz. From the aspect of frequency, the higher frequency can better characterize the wear process of the tool tip, but there are some differences in the failure point. However, the lower frequency is not significant for the wear process of the tool tip. In summary, the cutting parameters have little effect on the effectiveness and accuracy of the tool wear. It is a reliable method to analyze the tip wear by the amplitude variation of the sensitive operational mode.

(ii) The difference points

When the cutting parameters remain constant, the natural frequency will shift approximately 6 Hz due to the tool nose wear. Then, it offsets after reaching the limit value. However, for a sensitive mode of 85 Hz, the natural frequency is substantially no longer offset after the wear failure point. An important conclusion in this section is that the cutting parameters have little effect on the amplitude of the sensitive mode. Therefore, the method of tool tip wear, which is independent of the cutting parameters, is characterized by the amplitude of the sensitive mode.

4 Machining applications based on dynamic sensitivity

The stable wear stage of the tool tip can be judged by the frequency amplitude of the sensitive mode and then combined with the roughness of the workpiece surface. The aim is to optimize the processing.

4.1 Tool wear rate analysis

4.1.1 Effect of cutting parameters

For convenience, the cutting tool in Section 3.1.1 is named the 1 wear tool, and in Section 3.1.2, the cutting tool is named the

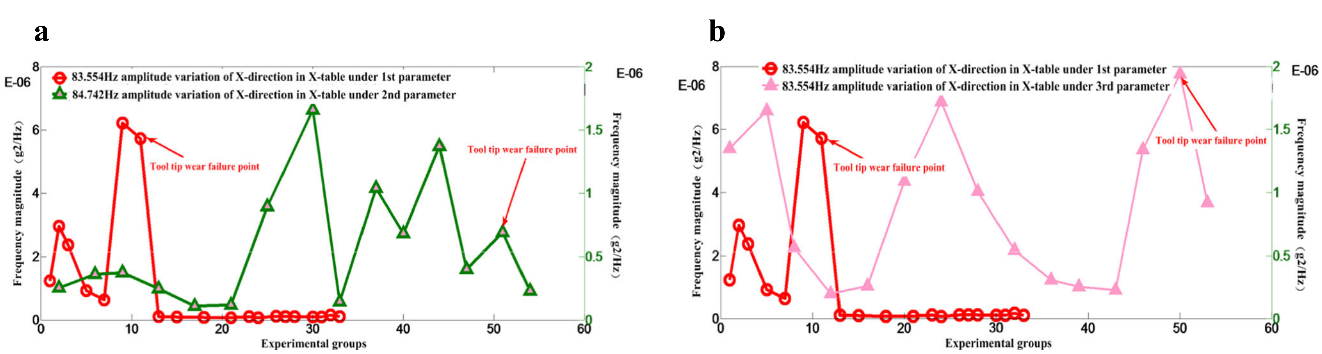

Fig. 21 Cutting time of wear tool. **a** First wear tool. **b** Second wear tool

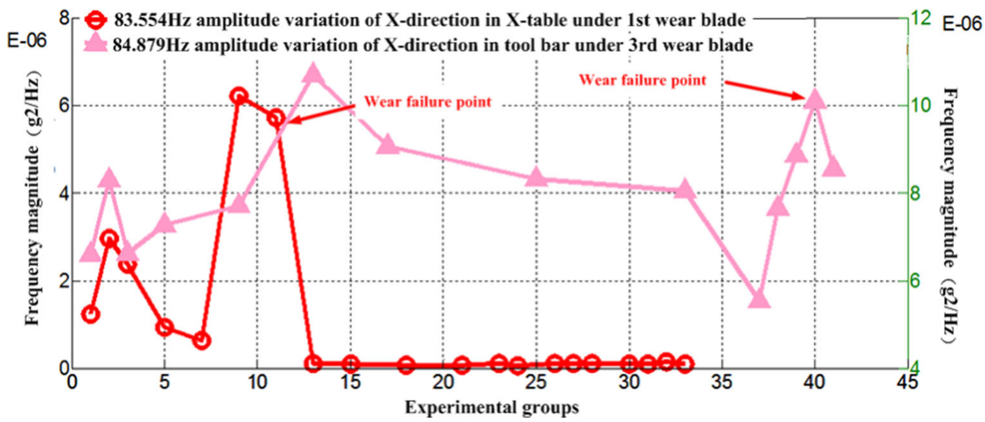

Fig. 22 Comparison of wear time between the first and third tool

second wear tool. Other cutting parameters are shown in Table 8.

As shown in Fig. 21, the first tool reaches the wear failure point when the 11th group is carried, and the second tool enters the accelerated wear stage when the 50th group is carried. For the first tool, the transverse cutting length is 68 mm, and the average feed rate of the first 11 groups is 21.36 mm/min, so the calculated cutting time is 35.019 min. For the second tool, the transverse cutting length is 65 mm, and the average feed rate of the first 50 groups is 29.755 mm/min, so the calculated cutting time is 109.225 min. The tool life of the second wear tool is expected to be at least 3.12 times the tool life of the first wear tool.

$$\text{Cutting speed ratio } v_{1-23} = \frac{v_1}{v_{23}} = \frac{30.3478}{20.4958} = 1.48 \quad (1)$$

$$\text{Average feed speed ratio } f_{1-23} = \frac{f_1}{f_{23}} = \frac{0.0952}{0.1675} = 0.57 \quad (2)$$

$$\text{Cutting depth ratio } a_{1-23} = \frac{a_1}{a_{23}} = \frac{0.4}{0.05} = 8 \quad (3)$$

From Eqs. (1), (2), (3), the cutting depth is found to have the greatest effect on the tool wear since the high cutting depth ratio. In other words, the tool wear speed is faster when the cutting depth increases. When the cutting allowance is small, the cutting depth is reduced, and the tool wear speed is reduced, which ensures that the dimensional accuracy is maintained at more cutting time.

4.1.2 Effect of workpiece rigidity

The influence of the rigidity of the workpiece is analyzed based on the first wear tool (Section 3.1.1) and the third wear tool (Section 2.3.1). Because the two cutting experimental conditions are similar, the only difference is that the first workpiece is in the cantilever state and the third workpiece is in the fixed state.

From Fig. 22, the first tool is worn very quickly, and the cutting time is 35.019 min when the 11th group is carried. However, the third tool is worn very slowly, and the cutting time is 120 min when the 40th group is carried. The tool life of the third is at least 3.43 times the tool life of the first. The rigidity of the workpiece has a great influence on the tool wear because the cutting speed of the third tool is greater than the cutting speed of the first tool. Fixing the workpiece can improve the rigidity and extend the tool life.

4.1.3 Effect of the cantilever length

The influence of the cantilever length is analyzed based on the second wear tool (Section 3.1.2) and the fourth wear tool (Section 2.3.2). The cutting parameters of the two cutting experiments are shown in Table 9, below.

From Fig. 23, the second wear tool is near the accelerated wear stage in the 50th group, and its cutting time is 110 min. However, the fourth wear tool reaches the wear failure point in the 66th group, and its cutting time is 198 min. Therefore, the fourth wear tool life is 2 times the second wear tool life, and the left cutting time of the second wear tool should be less than the left cutting time of the fourth tool. The fourth wear tool has some conditions such as greater cutting speed, longer workpiece cantilever length, and 40 Cr material that will reduce the tool life, which is opposite to the larger left cutting time of the

Table 9 Cutting conditions between the second and fourth wear tool

Cutting parameters	2nd tool	4th tool
Workpiece material	45 steels	40 Cr
Cutting speed (m/min)	20.4958	27.5432
Feed rate (mm/r)	0.1675	0.1190
Cutting depth (mm)	0.05	0.05
Cutting length (mm)	65	75
Cutting time (min)	2.19	3
Workpiece's cantilever length (mm)	100	120
Tool bar's cantilever length (mm)	37.35 mm	50 mm
Workpiece fixing method	Cantilever	Cantilever

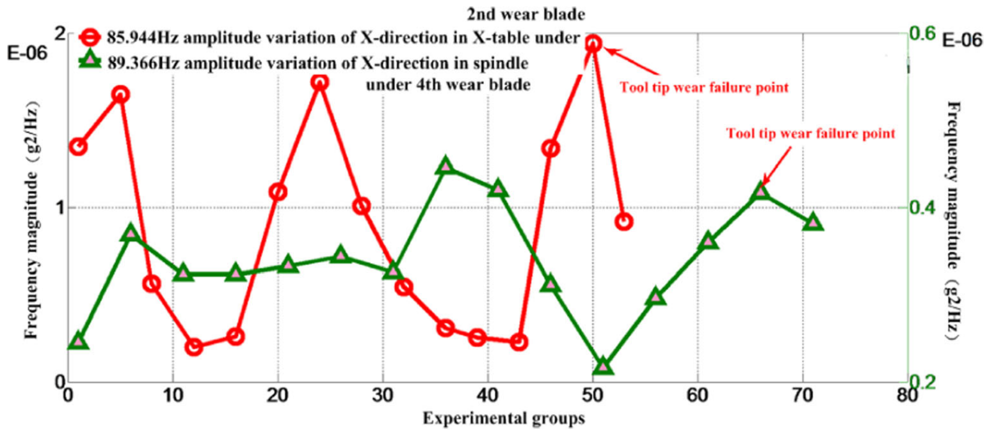

Fig. 23 Cutting conditions between the second and fourth wear tool

fourth tool. The shorter cantilever length will accelerate the tip wear because the second tool has a short cutting time.

A method that aims to slow down the wear and improve the cutting time is to increase the length of the cantilever. The increased length of the cantilever should be appropriate, because the cutting experiments of the larger cantilever length were not studied.

4.1.4 Conclusions

In the case where the processing time is not limited or where the precision turning process is not limited, the following four aspects can slow down the tip wear rate: (i) reduce the depth of the cutting, (ii) clamp the end of the workpiece, (iii) reduce the cantilever length of the workpiece if the workpiece is not clamped, and (iv) increase the appropriate cantilever length of the tool.

4.2 Processing design optimization

The stability phase can be judged according to the smaller amplitude of the vibration response in the direction of the main cutting force. The advantage of this stage is that the tool vibration is small, and the surface quality of the workpiece is better. Therefore, it is better to choose the main processing surface at this stage. The amplitude and roughness of the operational mode are studied to optimize the process design based on the vibration response data for the second wear tool.

From Fig. 24, the amplitude of the x-direction is 20 times larger than the amplitude of the y-direction in the stable wear stage with low amplitude. The 84.716 Hz in the x-direction and 84.703 Hz in the y-direction under cutting state are all from the 85 Hz under the static state. The tool is in the stable wear state from the 21st group to the 51st group. Its amplitude is very small and stable in the direction of the main vibration force. The cutting stage is defined as the low amplitude stabilization phase in the y-direction.

The roughness tester used in the experiment was Mitutoyo SJ 210 with the measuring speed of 0.5 mm/s and the resolution of 4 2.5 μm. The three original contour measurement parameters (Pa, Pq, Pz) will be obtained based on the unfiltered measurement data.

Figure 25a shows clearly that Pa is relatively stable (lower than 4.5 μm) from the 21st group to the 38th group. The surface quality of the workpiece is high during this process. Considering the amplitude in the y-direction of the main cutting force and the surface roughness, the process (group 21-group 51) is in the low amplitude stabilization phase of the

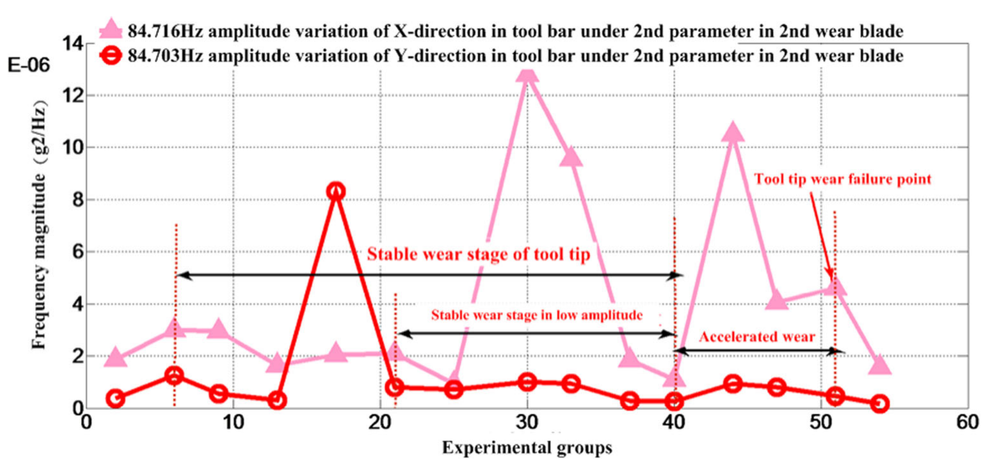

Fig. 24 The 85 Hz amplitude of the second wear tool in the x-direction and the y-direction

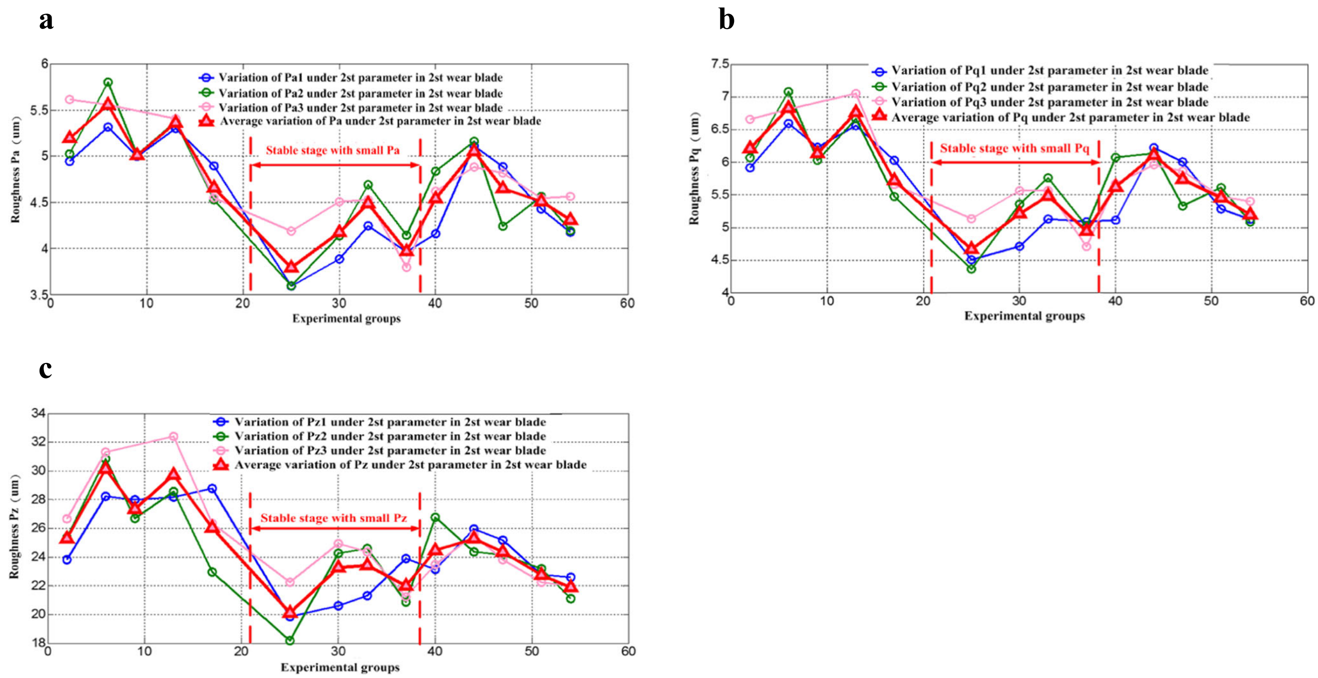

Fig. 25 The roughness parameters of the second worn tool. **a** Pa. **b** Pq. **c** Pz

vibration response and in the stable wear stage of the tool. The trends of Pq and Pz are consistent with the trends of Pa from Fig. 25b, c. The surface quality is qualified as the roughness parameter decreases after the 38th group.

It is best to arrange the high-quality surface processing at the low amplitude stable stage of the main cutting force and the steady wear stage of the tool. At the same time, the cutting depth and feed rate can also be increased to improve the cutting efficiency.

4.3 Cutting depth optimization

Cutting depth and tool wear affect the quality of the surface, so the cut depth needs to be optimized to meet the requirements of surface roughness.

The effects of cutting depth and tip wear on surface roughness were analyzed by using the fifth tool. The tool entered the steady wear stage after 19 groups of experiments, with only a small amount of wear. The cutting speed and feed rate remain constant except for cutting depth. Other parameters are shown in Table 10, below.

Table 10 Cutting parameters

Cutting parameter	Value
Material	45 steels
Workpiece cantilever length	100 mm
Tool cantilever length	51 mm
Each group feed length	65 mm
Cutting volume	111,101.591 mm^3
Cutting diameter	From 44.77 mm to 38.21 mm

Figure 26 presents the roughness parameters Pa, Pq, Pz, and their average value with the cutting time under 0.06 mm cutting depth. From Fig. 26, roughness changes less in the early stages, and the smaller wear of the stabilization phase will increase slowly in the later stages. The roughness will increase in the late stages more significantly under the 0.06 mm depth, especially Pa in Fig. 26a.

In summary, the tip wear will have an impact on the roughness under a small cutting depth. The greater the tip wear, the greater the roughness value. There is a certain correlation between roughness and tool wear in the case of a small cutting depth. In the precision cutting or in the tool wear stable stage, the cutting depth should be reduced to meet the surface quality requirements when the tool wear increases constantly.

5 Conclusions

This paper mainly studies the monitoring of the dynamic sensitivity-based tool condition and finds the factors that affect tool wear under operation. The conclusion is divided into three parts.

(i) Dynamic sensitivity method

There is consistency between the static modal sensitivity and the operational modal sensitivity. The cutting conditions do not affect the characterization of the tool workpiece system

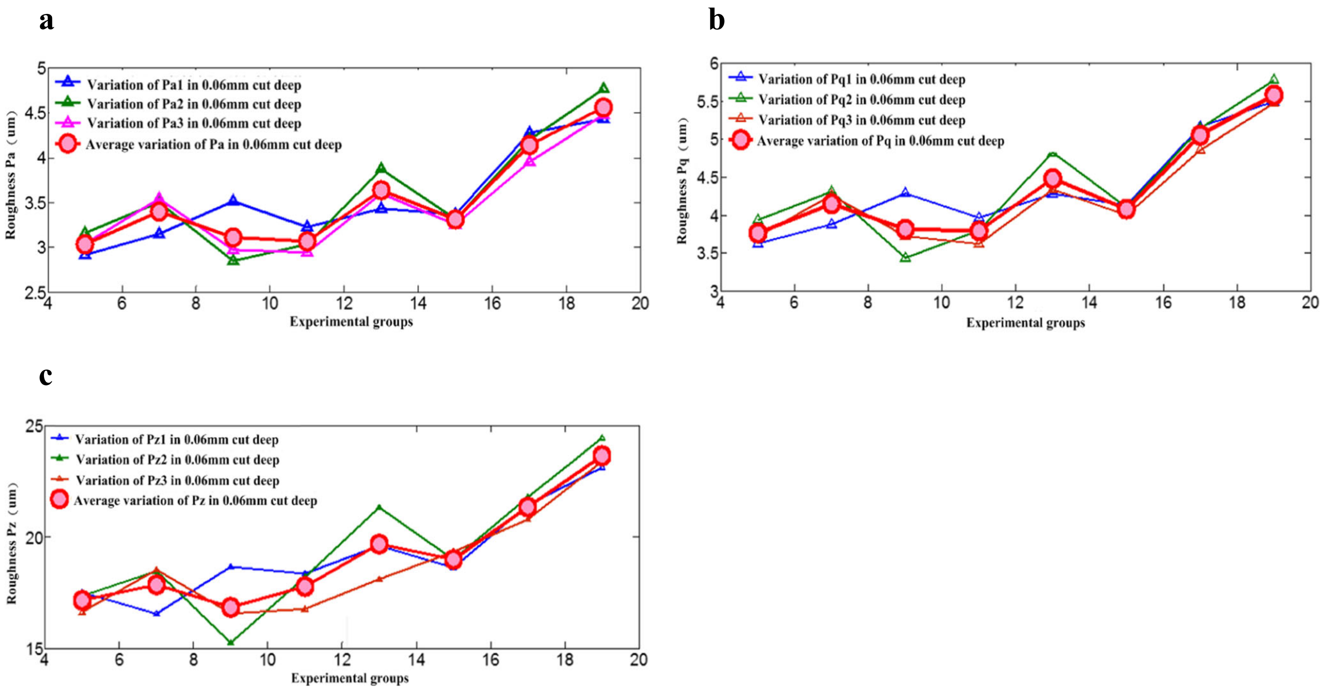

Fig. 26 The roughness parameters of the 5th worn tool. **a** Pa. **b** Pq. **c** Pz

that is expressed by the operational mode, especially the tool wear failure point. Regarding characterization, there are not only band differences but also direction differences and component differences. For example, the radial x-direction mode has the highest sensitivity to tip wear, especially 85 Hz in Section 2.2. In addition, modes excited by periodic excitation and rotational frequency are less sensitive to tool wear, while the modes excited by white noise excitation are more sensitive to tool wear.

(ii) Tool condition monitoring based on dynamic sensitivity

The sensitivity of dynamics is significantly different in the cutting direction, components, and frequency band. In terms of cutting direction, the cutting tool is better reflected by the tool wear than the spindle in the x-direction. The x-direction is more sensitive to the wear of the tool tip than the z-direction and the y-direction. In terms of measuring components, the measuring points of the x-table and spindle in 85 Hz are the most sensitive to tool tip wear. The amplitude changes of 85 Hz are most obvious on the workbench. The damping ratio changes of 85 Hz on the spindle reflect the most obvious. In terms of frequency band, the wear process of the tool can be characterized by the higher frequency, but it is not accurate near the failure point.

When the cutting parameters remain constant, the natural frequency will shift approximately 6 Hz due to tool nose wear. Then, it offsets after reaching the limit value. However, for a sensitive mode of 85 Hz, the natural frequency is substantially no longer offset after the wear failure point.

In summary, the cutting parameters have little effect on the effectiveness and accuracy of the tool wear. It is a reliable method to analyze the tool wear by the amplitude variation of the sensitive operational mode.

(iii) Machining applications based on dynamic sensitivity

In this paper, the influence of cutting depth, workpiece rigidity, and tool cantilever length on the tool wear speed was analyzed, and the measures to reduce wear rate are given. It is best to arrange the high-quality surface processing at the low amplitude stable stage of the main cutting force and the steady wear stage of the tool. At the same time, the cutting depth and feed rate can also be increased to improve the cutting efficiency.

In the cutting process with small cutting depth, smaller tool wear is beneficial to the surface quality of the workpiece. At this time, the cutting depth should be changed in real-time according to the wear to ensure the surface quality of the workpiece.

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References

1. Dimla DE Sr, Lister PM (2000) On-line metal cutting tool condition monitoring. : I: force and vibration analyses. Int J Mach Tools Manuf 40(5):739–768
2. Purushothaman S, Srinivasa YG (1994) A back-propagation algorithm applied to tool wear monitoring. Int J Mach Tools Manuf 34(5):625–631
3. Tansel IN, Mekdeci C, Mclaughlin C (1995) Detection of tool failure in end milling with wavelet transformations and neural networks (WT-NN). Int J Mach Tools Manuf 35(8):1137–1147
4. Masory O (1991) Detection of tool wear using multisensor readings defused by artificial neural network. Applications of Artificial Neural Networks II. International Society for Optics and Photonics 515–525
5. Rangwala S S, Dornfeld D (1987) Integration of sensors via neural networks for detection of tool wear states. Intelligent and Integrated Manufacturing Analysis and Synthesis 109–120
6. Dimla DE (1998) Multivariate tool condition monitoring in a metal cutting operation using neural networks. University of Wolverhampton
7. Rangwala S, Dornfeld D (1990) Sensor integration using neural networks for intelligent tool condition monitoring. J Eng Ind 112(3):219–228
8. Zhu K, San Wong Y, Hong GS (2009) Wavelet analysis of sensor signals for tool condition monitoring: a review and some new results. Int J Mach Tools Manuf 49(7–8):537–553
9. Lister P M (1993) On-line measurement of tool wear. University of Manchester Institute of Science and Technology
10. Bayramoglu M, Dungel Ü (1998) A systematic investigation on the use of force ratios in tool condition monitoring for turning operations. T I Meas Control 20(2):92–97
11. Schmitz TL, Smith KS (2008) Machining dynamics: frequency response to improved productivity. Springer Science & Business Media
12. Lim GH (1995) Tool-wear monitoring in machine turning. J Mater Process Tech 51(1–4):25–36
13. Aghdam BH, Vahdati M, Sadeghi MH (2015) Vibration-based estimation of tool major flank wear in a turning process using ARMA models. Int J Adv Manuf Technol 76(9–12):1631–1642
14. Chelladurai H, Jain VK, Vyas NS (2008) Development of a cutting tool condition monitoring system for high speed turning operation by vibration and strain analysis. Int J Adv Manuf Technol 37(5–6): 471–485
15. González-Laguna A, Barreiro J, Fernández-Abia A, Alegre E, González-Castro V (2015) Design of a TCM system based on vibration signal for metal turning processes. Procedia Eng 132:405–412
16. Rao KV, Murthy BSN, Rao NM (2016) Experimental study on tool condition monitoring in boring of AISI 316 stainless steel. Proc Inst Mech Eng Part B J Eng Manuf 230(6):1144–1155
17. Babu GP, Murthy B, Venkatarao K, Ratnam C (2016) Multi-response optimization in orthogonal turn milling by analyzing tool vibration and surface roughness using response surface methodology. Proc Instit Mech EngProc Inst Mech Eng Part B J Eng Manuf 231(12):2084–2093
18. Bhuiyan MSH, Choudhury IA (2015) Investigation of tool wear and surface finish by analyzing vibration signals in turning Assab-705 steel. Mach Sci Technol 19(2):236–261
19. Orhan S, Er AO, Camuşcu N, Aslan E (2007) Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness. NDT&E Int 40(2):121–126
20. Kalvoda T, Hwang YR (2010) A cutter tool monitoring in machining process using Hilbert–Huang transform. Int J Mach Tools Manuf 50(5):495–501
21. Sevilla-Camacho PY, Robles-Ocampo JB, Muñiz-Soria J, Lee-Orantes F (2015) Tool failure detection method for high-speed milling using vibration signal and reconfigurable bandpass digital filtering. Int J Adv Manuf Technol 81(5–8):1187–1194
22. Stavropoulos P, Papacharalampopoulos A, Vasiliadis E, Chryssolouris G (2016) Tool wear predictability estimation in milling based on multi-sensorial data. Int J Adv Manuf Technol 82(1–4):509–521
23. Rmili W, Ouahabi A, Serra R, Leroy R (2016) An automatic system based on vibratory analysis for cutting tool wear monitoring. Measurement 77:117–123