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ORIGINAL ARTICLE

Comprehensive effect of multi-parameters on vibration in high-speed precision milling

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Abstract

Precision milling processes have been widely applied to manufacturing parts in fields including automotive, aerospace, and precision machinery. Vibrations created in the milling process contribute significantly to machining accuracy and quality. While the direct and interaction effects of machining parameters on vibration amplitude have been analyzed statistically, the comprehensive effect considering machine tool non-cutting vibrations has not been fully explored. In this paper, the comprehensive effect of several machining parameters on the process vibration is studied and a cutting vibration signal-based optimization method is proposed. First, taking the frequency response function (FRF) and non-cutting rotating vibration into consideration, the spindle speed–related dynamic load in machining is studied to analyze the influence of machining accuracy. The main factors influencing the process dynamic performance are then studied using orthogonal experimental analysis of the vibration signal in milling. Finally, the comprehensive effect is determined and the optimal selection approach of machining parameters is put forward based on the experimental research of vibration in machining processes.

Keywords Milling · Vibration · Non-cutting · Machining parameters · Comprehensive

1 Introduction

Vibrations are an undesirable phenomenon in milling which adversely affect process stability, machining accuracy, and surface integrity. According to the observed factors, process vibration in milling can be classified into three categories: free vibrations, forced vibration, and chatter [1]. Generally, chatter occurs when the excitation frequency in cutting is equal or close to one of the natural frequencies of the machine tool, which is referred to as instable cutting. However, when the depth of cut is small, the influence of chatter vibration can potentially be disregarded [2, 3]. Therefore, the most significant issue limiting the performance of precision milling parts is the forced vibration caused by the dynamic load in process and machine tools [4]. Vibration is also dependent on the susceptibility of the cutting system and the generation of dynamic force in the cutting process [5]. While there is a widespread application of precision milling, many challenges remain in the process of machining components [6, 7]. To investigate dynamic characteristics in the milling process, the system structural dynamic performance, dynamic load, and the induced process vibration must all be considered.

Research into structural dynamics has predominantly focused on spindle dynamics and workpiece dynamic performance. Filiz et al. developed analytical models for dynamics of micro-scale cutting-tools and experimental models for an ultra-high-speed spindle [8], while Chen et al. proposed an evaluation process to identify the key parameters of a spindle system, determining that the spindle error is the main factor affecting the accuracy of the actual machining [9]. Additionally, Long et al. investigated the speed-dependent dynamic characteristics of ball bearings to study the frequency response function of the tooltip [10]. With the increasing popularity of thin-walled parts [11], researchers have also analyzed the structural dynamic performance of the workpiece system. Meshreki et al. presented a novel dynamic formulation of typical thin-walled pockets encountered in aerospace structures, which can predict the dynamics of pocket structures under sinusoidal, impact, and machining loads [12]. A

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brief review of the literature indicates dynamic performance evaluation of machine tool structures has been conducted and shows that structural dynamic characteristics determine the anti-vibration character, while dynamic load is the excitation source of vibration. Research into forced vibration illustrates that the unavoidable phenomenon of vibration is a key factor for surface finish, so the mechanism of milling processing must be further studied.

In the field of milling dynamic load, research works have mainly focused on the modeling and measurement of dynamic forces. Liang et al. presented the establishment of a closed-form expression for dynamic forces as explicit functions of cutting parameters and tool and workpiece geometry in milling processes [13]. Mativenga et al. presented a new method basis for modeling dynamic forces from the static component and harmonic contributions [14]. Moradi et al. developed an extended dynamic model of peripheral milling process including process damping, structural, and cutting force non-linearities, by using experimental coefficients [15]. Albertelli et al. studied the dynamical model of the machine tool spindle system to obtain the cutting forces with an in-process model-based estimator [16]. Grossi et al. found that dynamic cutting force coefficients change appreciably with spindle speed as mechanics of cutting change and then carried out a deep investigation of cutting force coefficients to estimate cutting force and tool tip vibrational behavior [17]. In addition, dynamic force has been identified by using acceleration signals in the milling process, further demonstrating the relationship between dynamic force load and vibration response [18]. The works focus on dynamic characteristics in the milling process, including machine tools and machining processes. It is therefore necessary to comprehensively investigate the influence of the structural dynamic performance and the process dynamic load on milling vibration.

Structural dynamic performance and process dynamic load will both affect vibrations in milling. Considering dynamic force and vibration response, Jalili et al. studied the influences of axial depth of cut, cutting tool diameter, cutting tool length, and the number of cutter teeth, on the frequency response of tooltip vibrations by using a 3D non-linear dynamic model of the milling process [19]. Liu et al. also proposed a method to study the effect mechanism of radial depth of cut on cutting vibration based on excitation and dynamic stiffness [20]. Ma et al. researched the effect of cutting areas and cutting direction on the variation of force and vibration in high-speed milling of a TC4 curved surface [21]. Sivasakthivel et al. developed statistical prediction model terms of tool geometrical parameters and machining parameters to study the influence of machining parameters on vibration amplitude and their sensitivity [22]. These structural dynamics and machining parameters reflect the process vibration and subsequently the workpiece finish quality as surface roughness and dimensional accuracy.

Cutting vibration is determined by the cutting force and the FRF under operational conditions. Similar to the machining force, heat, and residual stress [23–25], vibration is influenced by parameters such as spindle speed, feed rate, and depth of cut. Scholars have conducted several works on vibration analysis and vibration reduction in milling and analyzed the effects of machining parameters on vibration amplitude. However, the comprehensive influence mechanism of multi-parameters on vibration is still not adequately understood.

In this paper, the comprehensive effect of several machining parameters on the process vibration is studied by applying experimental research on the vibration of the machining process. An optimal selection approach of machining parameters is then presented. Taking the frequency response function and non-cutting rotating vibration into consideration, the spindle speed–related dynamic load in machining is first studied to analyze the influence of machining accuracy. Employing orthogonal experimental analysis of the vibration signal in milling, the main factor influencing the process dynamic performance is then examined. Finally, the comprehensive effect of the machining parameters is determined and an optimization method for machining parameters is proposed based on the study.

2 Analysis of milling dynamics

The dynamic milling process is simplified as a two-degrees-of-freedom system which is expressed in two directions (X direction is the feed direction, Y direction is perpendicular to the feed direction), as shown in Fig. 1. For the milling process, the governing equation can be described as [26]:

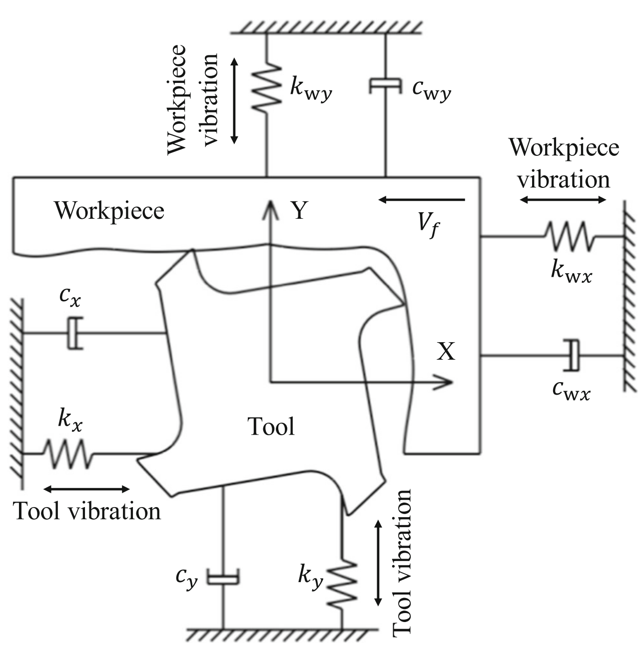

Fig. 1 Model of dynamic milling process

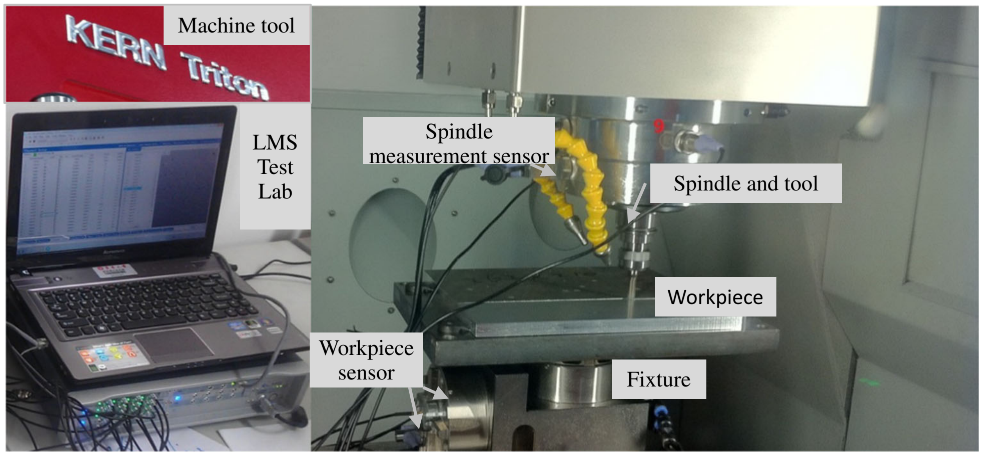

Fig. 2 Experimental setup

$$\mathrm{M}_x\ddot{X}(t) + \mathrm{C}_x\dot{X}(t) + \mathrm{K}_xX(t) = F_x(t) \quad (1)$$
$$\mathrm{M}_y\ddot{Y}(t) + \mathrm{C}_y\dot{Y}(t) + \mathrm{K}_yY(t) = F_y(t)$$

where $F_x(t)$and$F_y(t)$ represent the milling forces, and M, C, and K are modal mass, equivalent damping coefficients, and elastic coefficients, respectively, at the two directions. In the view of kinematics, the periodic variation of the relative displacement between the tool and workpiece leads to the dynamic force and contributes to the vibration of the tool.

Regardless of the theoretical model [27–29] or empirical model [30, 31] used for milling force, dynamic milling force is related to the several machining parameters. According to the vibration excitation theory, the vibration in the process is comprehensively affected by the multi-parameters. Firstly, in the field of frequency domain, it is known that the main frequency of the spindle is the spindle speed [14]. When the vibration acceleration signal is tested, the acceleration amplitude at the main frequency after fast Fourier transform (FFT) can be applied to analyze the dynamic performance. Assuming the displacement and the force in Eq. (1):

$$X(t) = Xe^{i\omega t} \quad (2)$$

$$F(t) = Fe^{i\omega t} \quad (3)$$

The velocity and acceleration can then be written as

$$\dot{X}(t) = i\omega Xe^{i\omega t} \quad (4)$$

$$\ddot{X}(t) = -\omega^2 Xe^{i\omega t} \quad (5)$$

Considering positive frequencies and a single-system configuration, substituting in Eq. (1) gives:

$$\begin{aligned}(-\omega^2 M_x + i\omega C_x + K_x)Xe^{i\omega t} = F_x e^{i\omega t}\\ (-\omega^2 M_y + i\omega C_y + K_y)Ye^{i\omega t} = F_y e^{i\omega t}\end{aligned} \quad (6)$$

When measurements are performed, the frequency response functions are denoted as:

$$\begin{aligned}\frac{X}{F} = \frac{1}{-\omega^2 M_x + i\omega C_x + K_x}\\ \frac{Y}{F} = \frac{1}{-\omega^2 M_y + i\omega C_y + K_y}\end{aligned} \quad (7)$$

The magnitude and phase parts of the frequency response function emphasize key features of forced vibration: (1) the forced vibration occurs at the frequency of the exciting force; (2) the size of the motion compared with the force (the magnitude) and the time delay between when the force reaches its maximum and the displacement reaches its maximum (the phase) depend on the frequency of the exciting force and the natural frequency of the system [32].

However, as the vibration displacements directly correspond to accuracy, it is difficult and inaccurate to calculate the vibration displacement values directly in time domain. The frequency-domain integration method is more precise for calculating the vibration displacement values. Firstly, the acceleration signal should be transformed from time-domain

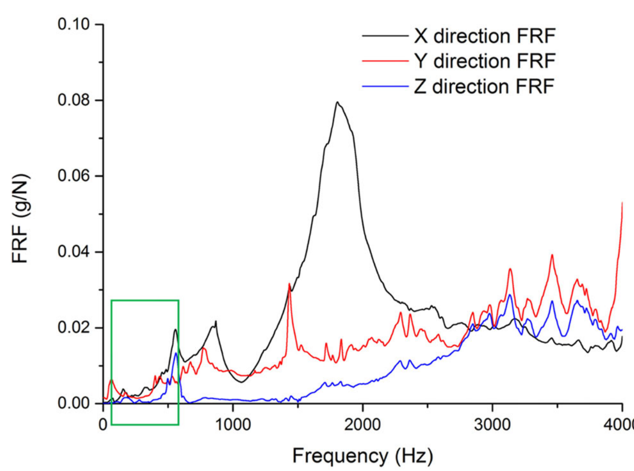

Fig. 3 FRFs of the spindle head measurement points in the impact test

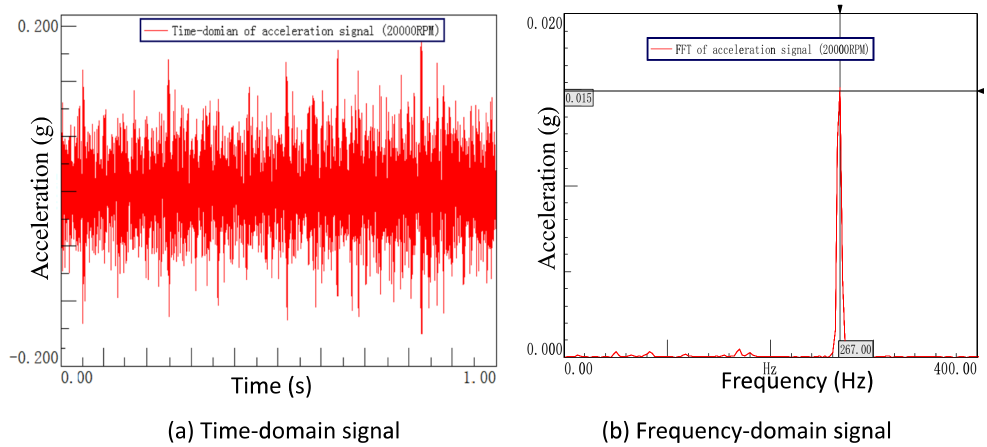

Fig. 4 Recorded vibration acceleration and its FFT results (20,000 rpm)

into frequency-domain by Fourier transform; the Fourier component coefficients in the frequency-domain are integrated. The Fourier component of acceleration signal at a certain frequency ω is expressed as:

$$a(t) = \ddot{X}(t) = Ae^{i\omega t} \tag{8}$$

When the initial velocity and displacement components are 0, the velocity signal component and displacement component are respectively expressed as:

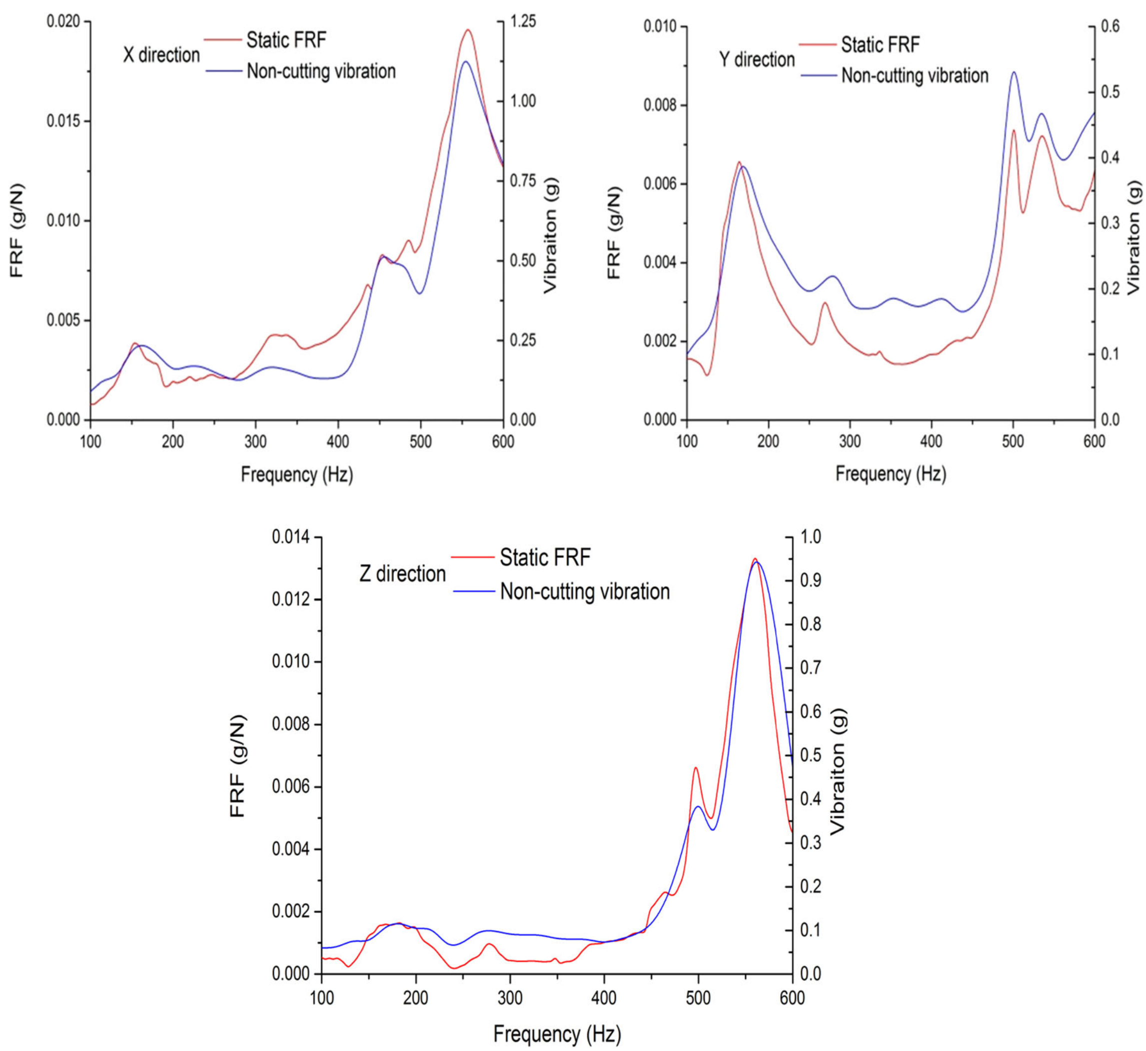

Fig. 5 Comparison of FRFs and non-cutting vibration

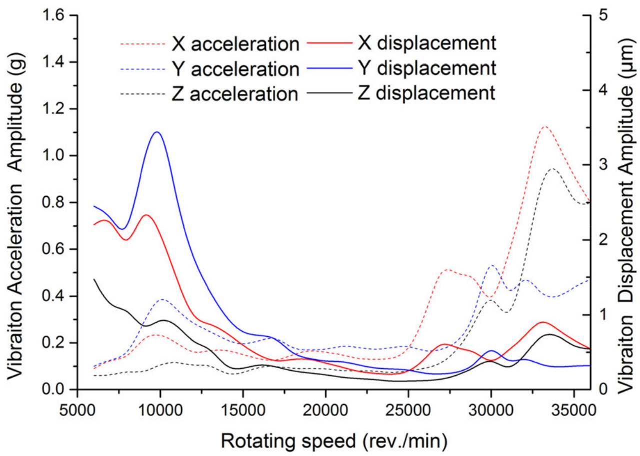

Fig. 6 Amplitude of vibration acceleration and converted displacement

$$v(t) = \dot{X}(t) = \int_0^t Ae^{i\omega t}d\tau = \frac{A}{i\omega}e^{i\omega t} = Ve^{i\omega t} \tag{9}$$

$$s(t) = X(t) = \int_0^t \left(\int_0^t Ae^{i\omega t}d\tau\right)d\tau = \int_0^t \frac{A}{i\omega}e^{i\omega t}d\tau = -\frac{A}{\omega^2}e^{i\omega t} = Se^{i\omega t} \tag{10}$$

As phase errors occur in frequency domain integration, this provides a sufficient method when phase information is not required. For discrete data points, the calculation formula of the velocity and displacement are:

$$v(r) = \sum_{k=0}^{M-1} \frac{1}{i \cdot 2\pi k \cdot \Delta f} F(k)A(k)e^{i \cdot 2\pi k \cdot r/M} \tag{11}$$

$$s(r) = \sum_{k=0}^{M-1} -\frac{1}{(2\pi k \cdot \Delta f)^2} F(k)A(k)e^{i \cdot 2\pi k \cdot r/M} \tag{12}$$

where

$$F(k) = \begin{cases} 1 & (f_l \le k\Delta f \le f_u) \\ 0 & \text{(other)} \end{cases} \tag{13}$$

f_l, f_u are lower cutoff frequency and upper cutoff frequency, respectively; *A(k)* is the Fourier transform of *a(T)*; Δf is the frequency resolution.

3 Experimental setup

As shown in Fig. 2, milling experiments were conducted on KERN TRITON. The vibration acceleration signals were obtained by Kistler Annular Ceramic Shear Accelerometer (Type 8784A5 and 8762A5) with a frequency response of 0.5 to 6000 Hz and a range of 5 *g*. The signals of vibration were recorded before, during, and after steady-state milling with LMS SCADAS Mobile. The frequency response functions of the tool were collected and studied in the impact experiments using a PCB hammer model 086C04.

Vibration analysis employed in this paper is based on non-cutting vibration of the machine tool and self-excited vibration caused by cutting force in milling, and it is in the mode of chatter free. A bandpass filter was applied to the process vibration signal to cut off the influence of static force and the huge vibration energy at high frequency. The frequency-domain integration method was then applied to compare the vibration displacement amplitude. The bandwidth was 4096 Hz and the frequency resolution was 0.5 Hz during the experiment.

4 Results and discussion

4.1 Non-cutting vibration analysis

The dynamic performance of milling processes includes two aspects, the machine tool characteristics and the cutting load-related performance. To investigate the non-cutting performance of the milling machine tool, the FRF test and the non-cutting rotating vibration test were conducted. In the experiments, the static FRFs of the spindle head measurement points in *X*, *Y*, and *Z* directions were obtained by impacting the tool point from *X*, *Y*, and *Z* directions, respectively. The results are shown in Fig. 3, illustrating the vibration resistance ability in the cutting process.

To obtain the dynamic load in a non-cutting process, the rotating vibration test was carried out in the rotating speed range of 6000 to 36,000 revolutions per minute (RPM). The maximum rotating speed of the machine tool was 38,000 rpm. The vibration of measurement points was recorded synchronously in stable non-cutting rotating process and the vibration amplitude at the main frequency (corresponding to 100 to 600 Hz) was calculated by FFT of the acquired vibration signal (Fig. 4). To determine the relationship between the static FRF and non-cutting vibration, the two curves were displayed in one figure with a frequency of 100 to 600 Hz (Fig. 5).

As illustrated in Fig. 5, the two curves display the same tendency in the analysis frequency ranges, indicating that the vibration response in a non-cutting rotating process is directly related to the FRF. While there is no cutting load, the vibration

Table 1 Cutting parameters and their levels

Factors	Levels		
	1	2	3
A: Spindle speed n (r/min)	12000	16000	20000
B: Feed rate v_f (mm/min)	1500	2000	2500
C: Axial cutting depth α_p (mm)	0.2	0.4	0.6

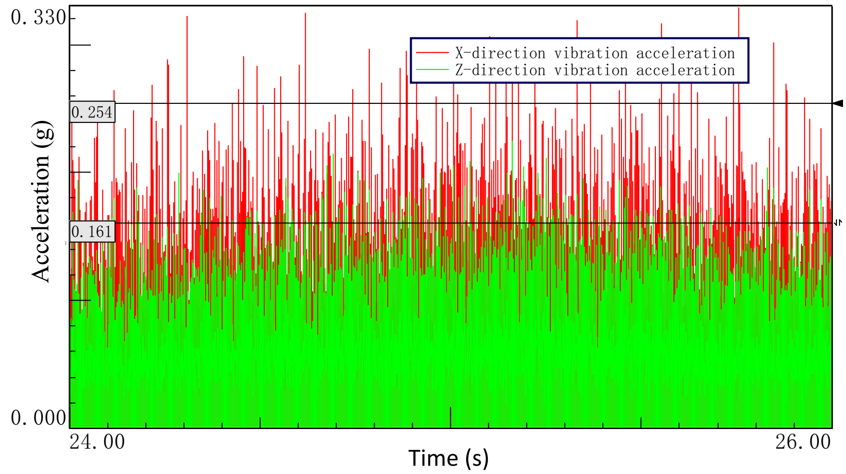

Fig. 7 Signal of vibration acceleration (exp. no. 1)

can be regarded as a special relation conversion of vibration and dynamic force load. As in Eq. (7) in frequency-domain, the non-cutting dynamic force load at the main force can be estimated. The dynamic load is the comprehensive effect of the bearing, spindle, and milling tool.

To study the effect of non-cutting vibration on machining accuracy, the vibration acceleration was converted by displacement by applying Eqs. (11–13). The results are shown in Fig. 6, illustrating the vibration displacements in X, Y, and Z directions in the rotating speed range. Though the vibration signal is acquired at spindle head measurement point and the displacement cannot stand for the tool vibration deformation, the findings indicate the machining stability and machining accuracy. It is also determined that selecting a suitable spindle speed in the rotating speed range can ensure vibration acceleration and displacement is relatively small.

4.2 Effect of machining parameters

To investigate the effect of the machining parameters, milling processes were performed using a workpiece of aluminum alloy 7050-T7451 with a size of 249× 197× 8 mm. This particular alloy is used in the aerospace industry and has the following chemical composition: Al 88.305%, Co 2.3%, Cr 0.4%, Fe 0.15%, Mg 2.25%, Mn 0.1%, Si 0.12%, Ti 0.06%, Zn 6.2%, and Zr 0.115%. A carbide grade end-mill tool with a diameter of 6.0 mm was used in the experiments. This tool was composed of four flutes, a rake angle of 15°, a clearance angle of 6°, and a helix angle of 30°. The tool was new and carefully selected for the purpose of this study. The machining parameters of milling processes were chosen as shown in Table 1 to effectively illustrate the analysis, and an orthogonal experiment table with three factors and three levels was adopted. The factors of A, B, and C respectively represent spindle speed n (r/min), feed rate v_f (mm/min), and axial cutting depth α_p (mm). The level of input parameters was selected on the basis of literature review, preliminary experimentation, recommended machining parameters for the carbide grade end-mill tools, and empirical parameters of aluminum alloy 7050-T7451 processing.

The L9(3^4) orthogonal table was employed for the test. A total of nine groups of tests was required, and each group of tests was carried out three times. The experimental tests were performed using a machining operation of down milling

Table 2 Orthogonal test results

Exp. no.	Factors			Vibration acceleration	
	n (r/min)	v_f (mm/min)	α_p (mm)	X direction (g)	Z direction (g)
1	12000	1500	0.2	0.254	0.161
2	12000	2000	0.4	0.417	0.156
3	12000	2500	0.6	0.515	0.221
4	16000	1500	0.4	0.532	0.273
5	16000	2000	0.6	0.624	0.281
6	16000	2500	0.2	0.432	0.182
7	20000	1500	0.6	0.68	0.533
8	20000	2000	0.2	0.587	0.289
9	20000	2500	0.4	0.668	0.413

Table 3 ANOVA results for vibration acceleration in X direction

Source	Sum of squares	DF	Mean square	F	P
Corrected Model	0.150[a]	6	0.025	23.593	0.041
A: Spindle speed n (r/min)	0.094	2	0.047	44.234	0.022
B: Feed rate v_f (mm/min)	0.005	2	0.003	2.551	0.282
C: Axial cutting depth α_p (mm)	0.051	2	0.025	23.993	0.040
Error	0.002	2	0.001		

Notes: R squared = 0.986 (adjusted R squared = 0.944)

around a rectangular workpiece under dry conditions. For the acquisition of vibration produced during the milling tests, three accelerometers were placed on spindle head measurement points (Fig. 2). Vibration acceleration was collected as shown in Fig. 7, and the average value was taken as the test result. The orthogonal test results are provided in Table 2. Vibration acceleration signal along the X and Z directions were measured, while Y direction was the feeding direction. As the material was removed along the feed direction, the vibration in the feed direction did not affect the machining accuracy and quality; thus, the vibration signal in the Y direction is not compared in this study.

To identify the influence degree and significance level of three milling parameters on vibration acceleration, IBM SPSS Statistics software was used to analyze the orthogonal test results. The results of the analysis of variance (ANOVA) performed at 95% confidence level are presented in Tables 3 and 4.

An ANOVA summary table is commonly used to summarize the test of the significance factors. If the value of 'P' in the ANOVA table is less than 0.05, then the model and the factors are said to be significant. Tables 3 and 4 show that the model is significant and spindle speed (A) and axial cutting depth (C) have a significant effect on the milling vibration acceleration in X and Z directions, while feed rate (B) is insignificant.

Furthermore, to analyze the effects of the milling parameters on milling vibration, the test data were further analyzed in Minitab software. The main effects of milling parameters are shown in Fig. 8, showing that both spindle speed and axial cutting depth have a direct relationship with vibration acceleration. Minitab creates the main effects plot by plotting the means for each value of a categorical variable. A line connects the points for each variable and illustrates whether a main effect is present for a categorical variable. Minitab also draws a reference line at the overall mean. When the line is horizontal (parallel to the x-axis), there is no main effect present and the response mean is the same across all factor levels. When the line is not horizontal, there is a main effect present and the response mean is not the same across all factor levels. The steeper the slope of the line, the greater the magnitude of the main effect. According to the F value and P value in Tables 3 and 4 and the main effect plots in Fig. 8, it can be seen that the influence order of the three milling parameters on the cutting vibration is as follows: A (spindle speed) > C (axial cutting depth) > B (feed rate). Consistent with the research results in Sivasakthivel's study [5], this mechanism is further investigated in this work.

As in Fig. 8, within a given range of test cutting parameters, the spindle speed n has the greatest effect on the cutting vibration signal.

(a) With the continuous increase of spindle speed, the cutting vibration gradually increases. On the one hand, the higher the spindle speed, the greater the friction between the tool and the workpiece, and the larger the cutting load fluctuation is; on the other hand, the process vibration contains signal components of the machine tool rotating vibration and differs according to the FRFs, which is consistent with the above analysis results of non-cutting vibration. The occurrence of both factors leads to the increase of vibration acceleration.

Table 4 ANOVA results for vibration acceleration in Z direction

Source	Sum of squares	DF	Mean square	F	P
Corrected model	0.123[a]	6	0.020	27.982	0.035
A: Spindle speed n (r/min)	0.086	2	0.043	58.709	0.017
B: Feed rate v_f (mm/min)	0.010	2	0.005	6.749	0.129
C: Axial cutting depth α_p (mm)	0.027	2	0.014	18.489	0.051
Error	0.001	2	0.001		

Notes: R squared = 0.988 (adjusted R squared = 0.953)

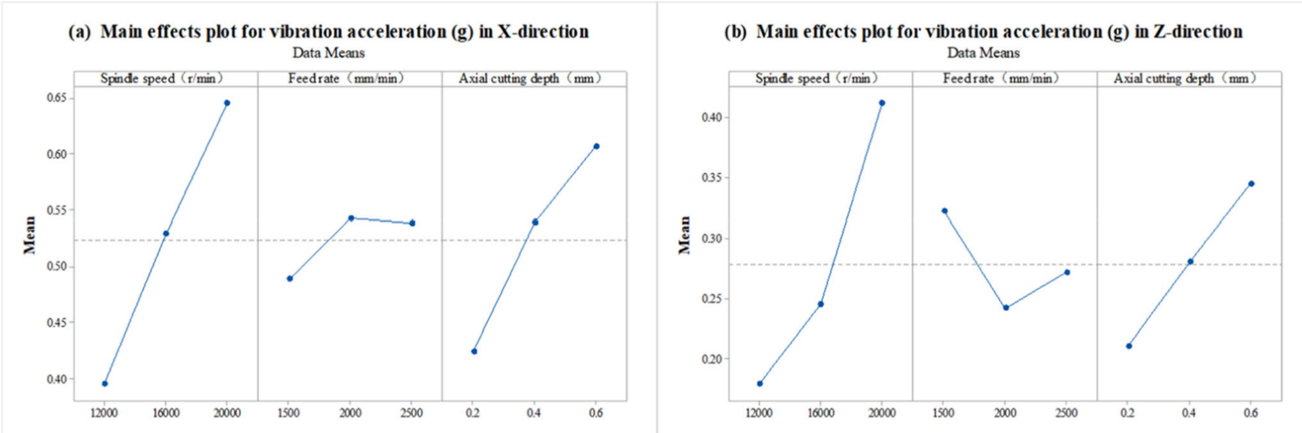

Fig. 8 Main effects plots for vibration acceleration in *X* and *Z* directions

(b) Feed rate has little effect on milling vibration. Generally, as the feed rate increases, the vibration will strengthen. The increase of feed rate will expand the cutting area and increase the deformation resistance, thus intensifying the vibration. However, it will also increase the cutting width, reduce the deformation coefficient and friction coefficient, improve the chip flow, and reduce the dynamic cutting force.

(c) The effect of axial cutting depth on milling vibration is obvious. As the milling depth increases, the increase of cutting depth will directly lead to the increase of cutting area and cutting force load, which will directly increase the cutting vibration.

5 Conclusions

This paper investigated the comprehensive effect of multi-parameters on vibration in high-speed precision milling by experimental method. The following conclusions can be drawn from the above investigation:

- Applying vibration signal analysis, the non-cutting vibration acceleration of the spindle can be approximately characterized by the vibration amplitude at the main frequency of the spindle rotating speed. The converted displacement values provide further reference.
- Through a comprehensive study of vibration excitation and impact testing, it is found that the FRF and non-cutting vibration display the same tendency with frequency changes, indicating that the vibration response in non-cutting rotating processes is directly related to the FRF.
- The effect of multi-parameters such as spindle speed, feed rate, and axial cutting depth on vibration amplitude is illustrated through L9 orthogonal milling experiments. The analysis of variance shows that the influence order of the three milling parameters on the cutting vibration is as follows: spindle speed > axial cutting depth > feed rate. Furthermore, the results indicating that spindle speed is the main factor correspond to the findings using non-cutting tests.

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