Identification Method of Modal Parameters of Machine Tools Under Periodic Cutting Excitation

**LING YIN[1], CHUNHUI LI[2], CHAO QIN[3], YILI PENG[3], JIARONG GU[3],
FEI ZHANG[1], SHUO LI[4], AND ZHIQIANG SONG[2]**

[1]School of Mechanical Engineering, Dongguan University of Technology, Dongguan 523808, China
[2]Beijing Zhenxing Institute of Metrology and Measurement, Beijing 100074, China
[3]School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[4]School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China

Corresponding author: Fei Zhang (zhangfei@dgut.edu.cn)

ABSTRACT The dynamics of a machine tool have an important influence on the quality and efficiency of the machining process. In this paper, the modal parameters identification method of machine tools under normal cutting excitation is proposed based on the fact that the random components in the cutting force can provide an effective excitation. However, the generated cutting force during machining contains strong periodic components and does not satisfy the white noise assumption. Directly applying the operational modal analysis (OMA) method will face serious harmonic interference. Therefore, it is difficult to ensure the accuracy of the identified parameters. The cepstrum editing method is proposed to eliminate the periodic component. And the modal parameters are extracted from the remaining signal by using the OMA method. The experimental results show that the proposed method works well under normal cutting conditions.

INDEX TERMS Cepstrum editing, cutting processing, harmonic elimination, machine tool, modal parameters.

I. INTRODUCTION

In general, increasing the material removal rate can increase the productivity of machine tools, but it can also cause chattering. Seguy and Campa *et al.* [1], Compean *et al.* [2], Urbikain *et al.* [3], [4] found that accurate identification of machine tool dynamics is the key to predict flutter boundaries. And numerous researches show that the dynamic characteristics of CNC machine tools under running conditions are very different from those under static conditions. Under this background, the research method of dynamic characteristics of machine tools based on the OMA method has been widely used. Ideally, the OMA method requires the excitation signal to be a white noise signal. However, the machine tool usually cutting the workpiece with a rotating tool, the cutting

The associate editor coordinating the review of this manuscript and approving it for publication was Min Xia.

force generated in the machining process is mainly a strong periodic signal, which becomes extremely difficult to directly identify the dynamic parameters with an OMA method under this condition.

In order to avoid the periodic effect of cutting force, scholars artificially create special cutting force signals, including the use of tools with special tooth distribution, cutting a workpiece with special feature, and controlling the machine tool for special movements with NC codes. Tounsi and Otho [5] used a single-tooth disc milling cutter to machine a long bar-shaped workpiece to generate a pulsed cutting force to excite the machine. Özşahin *et al.* [6] milled a workpiece with random bosses on a five-axis machining center to generate random excitations for the machine tool. In 2013, Li *et al.* [7] used a randomly rotating single-tooth disc milling cutter to cut a single-blade workpiece to generate a random pulse cutting force to excite the machine tool, and acquired the

modal parameters of the machine tool in the frequency band of interest. In 2016, Iglesias *et al.* [8] controlled the machine tool to constantly change the spindle speed while machining, in order to avoid the harmonic influence caused by the constant spindle speed, and corrected the milling stability lobe diagram with the identified modal parameters. At the same time, some scholars use the inertial force generated by the movement of the moving parts of the machine tool as the vibration source to stimulate the machine tool. In 2013-2015, scholars [9]–[11] excited the machine tool with the inertial force produced by the random feed movement of worktable and the spindle. In 2016, Liu *et al.* [12] used this method as a reference to verify the validity of the proposed current-based modal parameter identification method.

Although the above methods can identify the dynamic parameters of the machine tool under working conditions, however they are not performed under the normal machining situation and need artificial experimental conditions.

Scholars have also directly performed dynamic analysis on a machine tool under machining. In 2009, Zaghbani and Songmene [13] implemented a milling experiment with a straight shank end mill and identified the dynamic characteristics of the machining system through the vibration response of the spindle head. Two algorithms based on the OMA method were directly used to identify the modal parameters from the original acceleration signal. However, the excitation signal did not satisfy the white noise assumption and brought harmonic interference. To deal with the harmonics, the stability diagram in the x and y direction were superposed to distinguish whether the results are natural frequencies. A damping ratio threshold of 0.05% was also used to identify the harmonics. These two methods cannot fundamentally remove the harmonics, and are not able to solve the problem of missing the natural frequencies due to the interference of harmonics to the identification algorithm. In 2011, Özşahin *et al.* [6] also conducted normal cutting experiments in their research. They created specific tooth passing frequencies according to the interested band by setting different spindle speeds, so that the modes near the tooth passing frequencies would be excited. In 2013, Österlind *et al.* [14] used the laser displacement sensor to obtain the displacement of the tool under cutting conditions. Combined with the simulated cutting force, the FRF was synthesized, and the stability lobe diagram was obtained.

In addition to the periodic components caused by revolving motion of the tool, the cutting force generated during machining also contains random components due to the existence of hard points in the workpiece material and the relative vibration between the tool and the workpiece. Therefore, the vibration response also includes random components excited by the random component in cutting force, which contains the dynamic characteristics of the machine tool under machining conditions.

However, directly applying the OMA method to the original vibration signal will face severe harmonic interference due to the existence of strong periodic components in the vibration response. In addition, the original cutting force
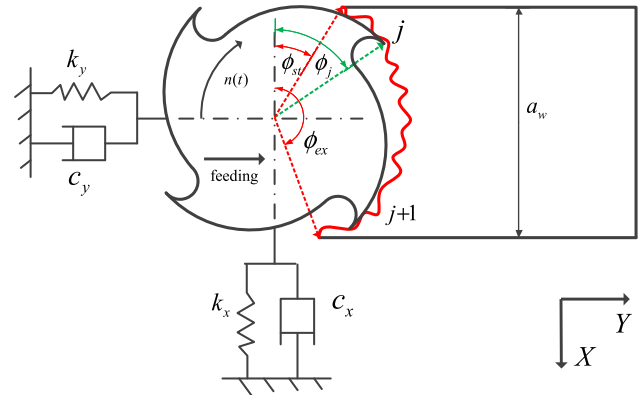

FIGURE 1. Schematic diagram of the milling process.

corresponding to the original response does not satisfy the white noise assumption, and its PSD cannot be assumed to be a constant. If the OMA method is applied directly, the accuracy of the identified parameters cannot be well guaranteed.

Therefore, to obtain the modal parameters under machining condition, it is not enough to only distinguish between the harmonic modes and the structural modes, but necessary to remove the periodic components from the original vibration response signal.

II. THEORETICAL BACKGROUND
A. EXCITATION CHARACTERISTICS OF CUTTING FORCE
The general milling process is shown in Figure 1. In the machine-tool-workpiece system, the tool mounted on the front end of the spindle can be regarded as a cantilever beam structure fixed at one end, and the terminal rigidity of tool is relatively small with two orthogonal degrees of freedom. In addition to feed movement during milling, the tool will also vibrate relative to the workpiece due to the excitation of cutting force, and the relative vibration causes changes in cutting volume, which in turn leads to fluctuations in cutting force. At the same time, there are randomly distributed hard spots in the workpiece material, which also leads to a certain level of random fluctuation of the cutting force. Figure 2 shows the cutting force signal in a milling processing of aluminum alloy material. It can be seen that the cutting force changes periodically in general, but it is an undesirable periodic signal with a certain degree of fluctuation.

Therefore, it can be considered that the cutting force generated during processing consists of two parts. The first part is the periodic component produced by the periodic rotary motion of the tool. This part with extremely high energy is the main component. Another part is the fluctuating component of cutting force caused by the relative vibration between the tool and the workpiece, and this part can be considered as a zero mean random signal [15]. The former part will cause the periodic forced vibration of machine tool, while the other part will provide the machine tool with a wide-band random excitation.
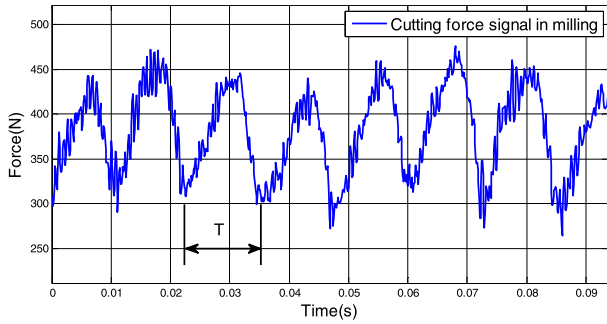
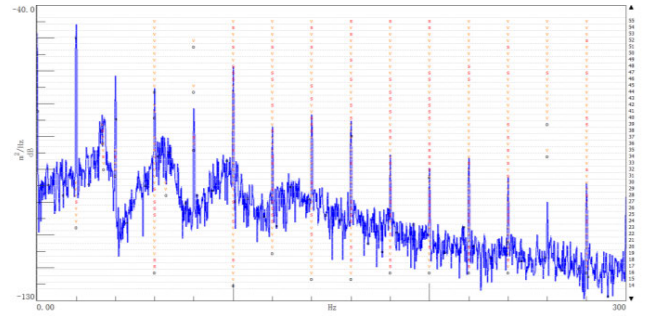**FIGURE 2.** Fluctuating cutting force in milling processing.

FIGURE 3. PSD of the simulated cutting force and vibration.

FIGURE 4. Interference of harmonics to modal parameter identification.

FIGURE 5. Principle of OMA under periodic cutting excitation.

Figure 3a shows the PSD of a typical cutting force signal with following features:

1) The low-amplitude part of the PSD shows the characteristics of wide frequency band and continuity because of the presence of random components in the cutting force;

2) Steep peaks (the high-amplitude part) with narrow bandwidth distribute discretely and massively at the fundamental and harmonic frequencies, this is caused by the periodic component in the cutting force.

Considering the machine tool as a linear structure with multiple degrees of freedom, the vibration response of the machine tool will include both periodic forced vibration component and random vibration component under the excitation of cutting force. Figure 3b shows a PSD of the typical cutting force excited vibration. The harmonic frequencies caused by periodic forced vibration are distributed throughout the frequency band, at the same time, peaks appeared at the modal frequencies of about 34Hz, 65Hz, 95Hz and 126Hz,
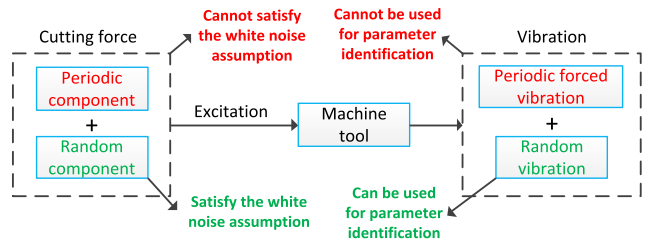
which were generally excited by the random component in the cutting force.

B. OPERATIONAL MODAL ANALYSIS OF MACHINE TOOL UNDER PERIODIC CUTTING EXCITATION

The OMA method is a modal parameter identification method based on response only, which requires that the structure is excited by a stational white noise signal. From Section A, it can be seen that the random components in the cutting force is a zero mean random signal, approximately satisfying the white noise assumption and can provide a broadband random excitation to the machine tool structure.

However, it is not able to directly use the OMA method to identify parameters due to the periodic component. As shown in Figure 4, the identification of modal parameters cannot be effectively performed under harmonic disturbances. The pole alignments do not appear at the natural frequencies (34Hz, 65Hz, 95Hz and 126Hz) but are almost all concentrated at harmonic frequencies. Therefore, to obtain the modal parameters under periodic cutting excitation, it is necessary to previously remove the periodic components from the original vibration response. The principle is shown in Figure 5, the procedure is illustrated in Figure 6.

C. REMOVAL OF PERIODIC COMPONENTS IN VIBRATION SIGNAL

1) CEPSTRUM AND ITS CHARACTERISTICS

The most general type of cepstrum, the "complex cepstrum", is given by the equation:

$$C_c(\tau) = F^{-1}\{\ln[F(f)]\} = F^{-1}\{\ln[A(f)] + j\phi(f)\} \qquad (2.1)$$
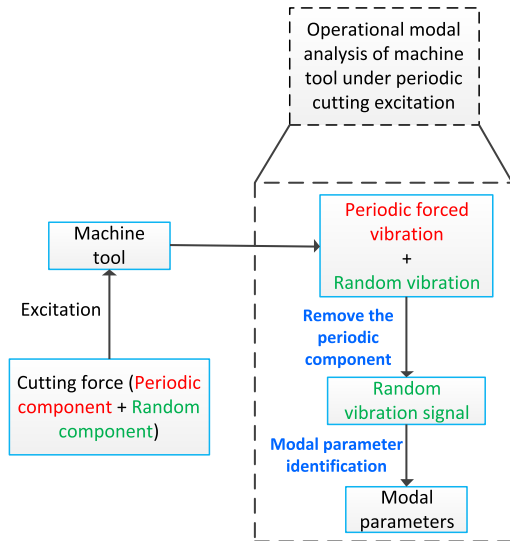
FIGURE 6. Procedure of OMA under periodic cutting excitation.

FIGURE 7. Milling vibration response and its real cepstrum.

where $F(f) = A(f)e^{j\phi(f)}$ is the complex spectrum of time signal, $A(f)$ and $\phi(f)$ are amplitude and phase, respectively. The complex cepstrum is reversible to a time signal, while if the cepstrum is based on the log amplitude only (ie $\phi(f)$ is set to zero) the result is the "real cepstrum":

$$C_r(\tau) = F^{-1}\{\ln|(F(f)|)\} = F^{-1}\{\ln[A(f)]\} \quad (2.2)$$

Under the excitation of the signal $f(t)$, the time domain response $y(t)$ of the linear system can be represented as the convolution of its impulse response function $p(t)$ and the excitation signal $f(t)$:

$$y(t) = f(t) * p(t) \quad (2.3)$$

Perform the Fourier transform on the two sides of the above equation to obtain the complex spectrum of the time domain response:

$$Y(f) = F(f) \cdot P(f) \quad (2.4)$$

Equation (3.4) can be further expressed as follows:

$$\begin{aligned}
Y(f) &= F(f) \cdot P(f) \\
&= A_f(f)e^{j\phi_f(f)} \cdot A_p(f)e^{j\phi_p(f)} \\
&= [A_f(f) \cdot A_p(f)] \cdot [e^{j\phi_f(f)} \cdot e^{j\phi_p(f)}] \\
&= [A_f(f) \cdot A_p(f)]e^{j[\phi_f(f)+\phi_p(f)]} \quad (2.5)
\end{aligned}$$

where $A_f(f), A_p(f)$ are the amplitude spectrum of the excitation signal and the impulse response function, respectively, $e^{j\phi_f(f)}$, $e^{j\phi_p(f)}$ are the phase spectrum of the excitation signal and the impulse response signal, respectively.

From equation (2.1) and (2.4), the complex cepstrum of the original time response signal is obtained:

$$\begin{aligned}
C_{cy}(\tau) &= F^{-1}(\ln[Y(f)]) \\
&= F^{-1}(\ln[F(f) \cdot P(f)]) \\
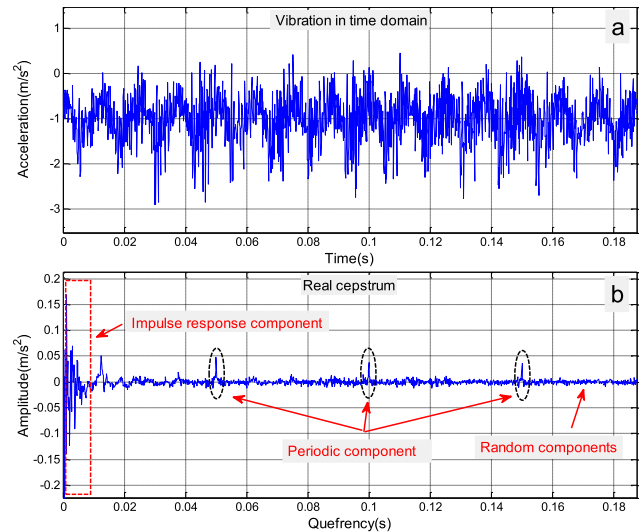&= F^{-1}(\ln[F(f)] + \ln[P(f)])
\end{aligned}$$

$$\begin{aligned}
&= F^{-1}(\ln[F(f)]) + F^{-1}(\ln[P(f)]) \\
&= C_{cf}(\tau) + C_{cp}(\tau) \quad (2.6)
\end{aligned}$$

where $C_{cf}(\tau)$, $C_{cp}(\tau)$ are the complex cepstrum of the excitation signal and the impulse response function, respectively. The real cepstrum of the original time response signal is obtained from equation (2.2) and (2.5):

$$\begin{aligned}
C_{ry}(\tau) &= F^{-1}\{\ln|(Y(f)|)\} \\
&= F^{-1}\{\ln[A_f(f) \cdot A_p(f)]\} \\
&= F^{-1}\{\ln[A_f(f)] + \ln[A_p(f)]\} \\
&= F^{-1}\{\ln[A_f(f)]\} + F^{-1}\{\ln[A_p(f)]\} \\
&= C_{rf}(\tau) + C_{rp}(\tau) \quad (2.7)
\end{aligned}$$

where $C_{rf}(\tau)$, $C_{rp}(\tau)$ are the real cepstrum of the excitation signal and the system impulse response function, respectively. From equations (2.6) and (2.7), it can be seen that in the quefrency domain, the system's vibration response is the sum of the cepstrum of its impulse response function and the cepstrum of excitation signal.

2) PERIODIC COMPONENT REMOVAL METHOD BASED ON CEPSTRUM

The real cepstrum of a milling vibration response is shown in Figure 7. It can be seen that the impulse response components including the modal information of the system are concentrated in the low quefrency band, discrete pulses corresponding to periodic forced vibration are concentrated at each cycle time point (e.g., 0.05s, 1.00s), and the random components are evenly distributed throughout the entire quefrency band. It is easy to separate the different components in the cepstrum, therefore, the method of cepstrum editing can be used to achieve the purpose of removing periodic components in the vibration signal.

The schematic diagram of performing the cepstrum editing [16] is shown in Figure 8.
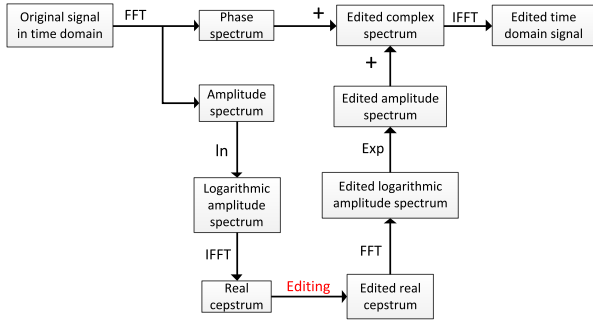
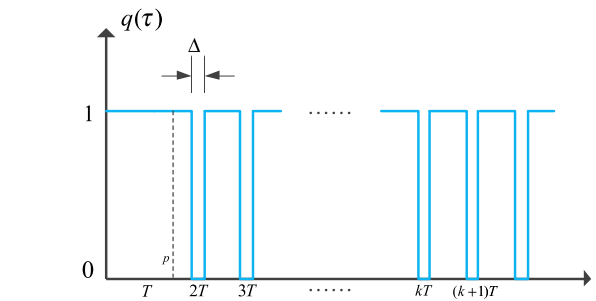FIGURE 8. Schematic diagram of performing the cepstrum editing.

FIGURE 10. Improved notch filter.

FIGURE 9. Filter in quefrency domain.

TABLE 1. Experimental conditions.

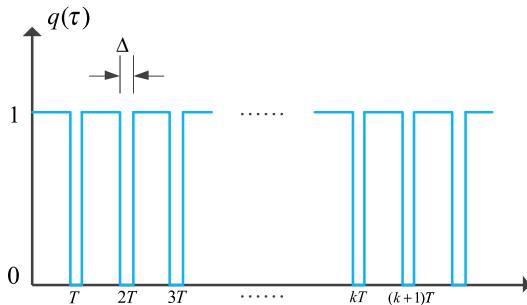|		
3-axis vertical machining center	Model	DM4600
	NC system	FUNACseries0iMate-MD
	Coolant	None
Tool	Type	Super hard straight shank helical end milling cutter
	Diameter	16mm
	Number of tool teeth	4
	Helix angle	40°

A notch filter $q(\tau)$ in quefrency domain is used to edit the cepstrum, as shown in Figure 9. T is the time interval between two discrete pulses in the quefrency domain, which is consistent with the period of the periodic component in the time domain. Under machining condition, the spindle speed of the machine and the number of teeth of the tool are all known, so the value of T can be conveniently calculated. $\Delta\tau$ is the filter width.

The edited real cepstrum of the vibration signal can be expressed as:

$$C_{r\_edited}(\tau) = q(\tau) \cdot C_r(\tau) \qquad (2.8)$$

It should be noted that when the period of the notch filter function used is too small, the cepstrum signal of the impulse response in the low quefrency band will also be partially removed. To ensure that the impulse response cepstrum signal will not be disturbed, a factor τ_p is used to improve the notch filter. When $\tau \leq \tau_p$, the value of $q(\tau)$ is always 1. The value of τ_p is determined according to the actual situation. The improved notch filter is shown in Figure 10.

III. EXPERIMENTAL VERIFICATION

In this section, impacting experiment and milling experiment were performed to verify the feasibility of the proposed method. All experiments were performed on the three-axis vertical machining center, and the rotary head was driven directly by a motor. The model is DM4600. Table 1 shows the technical parameters of the machine and tool used in the experiments. Figure 11 shows the experiment setup.
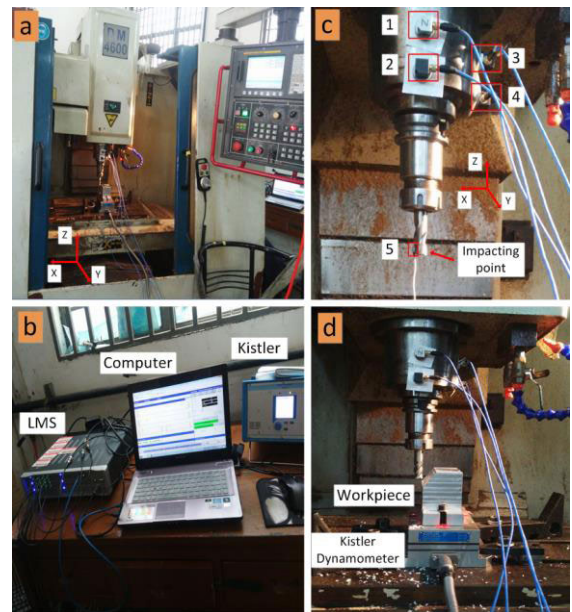
FIGURE 11. Experiment setup.

To ensure the accurate acquisition of the vibration signal of the spindle head in impacting and cutting tests, four accelerometers are attached to the spindle head (Figure 11c, 1-4). The type of accelerometers is PCB 356A16 (sensitivity, 100 mv/g; measurement range, ±50 g; frequency range (±5%), 0.5–5000 Hz; resonant frequency, ≥25 kHz). A micro acceleration sensor is attached to the tool point (Figure 11c, 5) to obtain the FRF of the spindle head with respect to the tool point. The type of accelerometer is DYTRAN 3224A1 (sensitivity, 10 mv/g; measurement range,

FIGURE 12. Mode stabilization diagram of X direction FRF in impacting test.

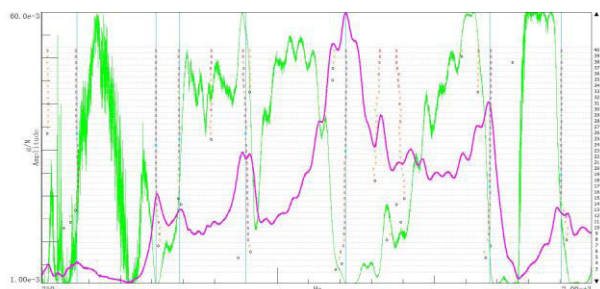± 500 g; frequency range ($\pm 5\%$), 0.3–20,000 Hz; resonant frequency, >95 kHz; weight, 0.2 g). The type of the hammer is DYTRAN 5800B4 (sensitivity, 2.2 mv/N; measurement range, $\pm$ 2224 N; resonant frequency, ≥ 75 kHz). A table dynamometer (Figure 11d, Kistler 9257B) was used to measure the cutting forces in cutting test. The cutting forces acted as the tool excitation signal.

A. EXPERIMENT SETUP

1) IMPACTING EXPERIMENT
   1) The hammer excites the tool point from X and Y directions. In order to reduce test errors, the FRFs from five repeated tests are averaged.
   2) Both the impact force of hammer and the vibration responses of tool point and four spindle head measurement points are recorded synchronously and processed by the acquisition and analysis system LMS Test. Lab.
   3) The sampling frequency is 8192Hz and the frequency resolution is 0.25Hz. The result of sensor 4 in Figure 11c was used to measure the vibration of the spindle head.

Using the experimental PolyMAX parameter identification algorithm in LMS Test. Lab, the modal parameters of the spindle head were obtained by the acceleration FRF of the spindle head with respect to the tool point. A mode stabilization diagram based on the impact experiments is shown in Figure 12. The red line represents the frequency response function, and the line curve represents the modal indicator function. The model order is 40 and the identification bandwidth is 250-2000 Hz. The identified modal parameters in X direction are shown in Table 2.

2) MILLING EXPERIMENT
   1) In the cutting experiments, the workpiece material is ZL105 aluminum alloy, the dimension in the X and Y direction is 70mm∗100mm, so the influence of the spindle position change on the modal parameters of the machine tool is negligible. The type of dynamometer is Kistler 9257B.
   2) Vibrations and forces of the cutting process were recorded synchronously by the acquisition and analysis system LMS Test. Lab (see Figure 11b). The Y direction was selected as feed direction, and down milling was used.

TABLE 2. Modal parameters of spindle head in impacting test.

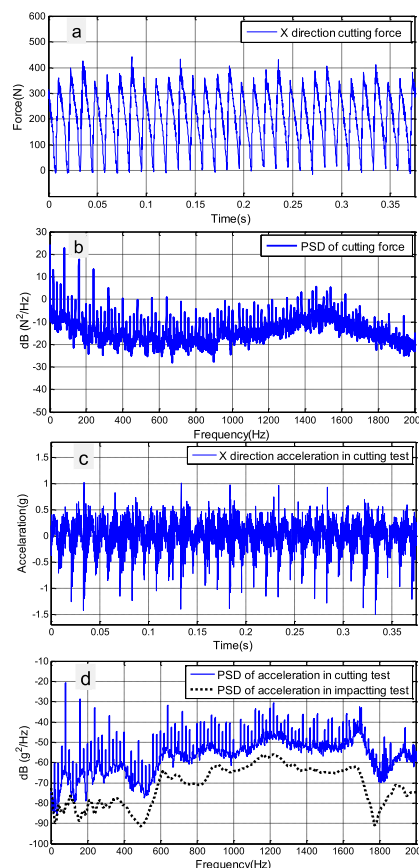| Modes	1	2	3	4	5	6	7
f(Hz)	361.12	613.12	687.80	899.07	1218.03	1677.22	1903.24
ξ(%)	7.40	2.81	2.45	2.41	5.20	1.69	1.48

FIGURE 13. Time signal and PSD of cutting force and spindle head acceleration in X direction.

3) The spindle speed is 1200rpm, radial cut width is 6mm, feed speed is 600mm/min, axial depth of cut is 3mm;
4) The result of sensor 4 in Figure 11c was used to measure the vibration of the spindle head. The sampling frequency is 8192Hz and the frequency resolution is 0.25Hz.

B. RESULTS AND DISCUSSIONS

1) SPECTRAL ANALYSIS OF CUTTING FORCE AND VIBRATION RESPONSE

The cutting force and acceleration signal of spindle head in X direction were taken for analysis. Their original time signal and PSD are shown in Figure 13. The PSD of the cutting force is shown in Figure 13b, it can be seen that harmonics of 20 Hz appear in the entire frequency band, which are caused by the periodic component in the cutting force. Meanwhile, the
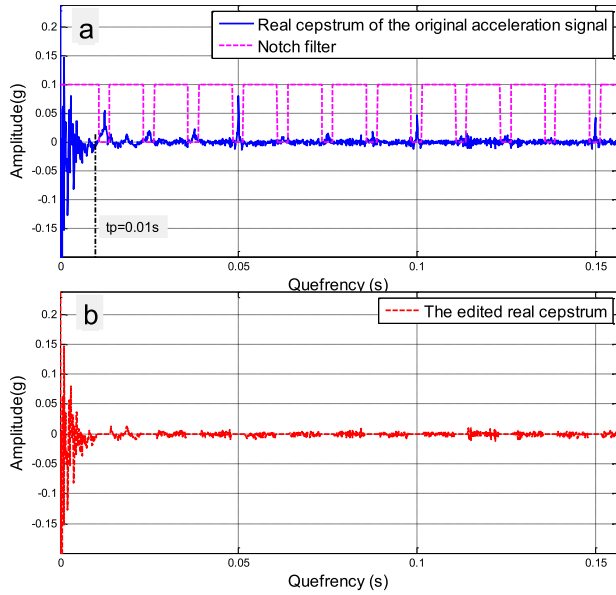
FIGURE 14. Real cepstrum of spindle head acceleration signal before and after editing.
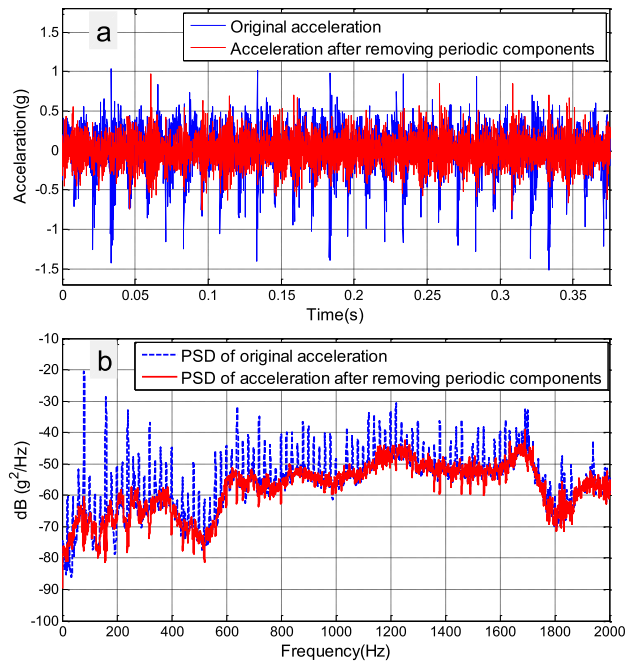

FIGURE 15. Acceration signal and PSD after harmonic elimination.

low-amplitude part of the PSD curve is relatively straight, especially between 200Hz and 1200Hz.Figure 13d shows the PSD of the acceleration of spindle head within 2000 Hz. Similarly, harmonics of 20 Hz appear in the entire frequency band, which are caused by the periodic forced vibration component in the vibration response. At the same time, the low-amplitude part of the PSD in milling test is very consistent with the PSD in impacting test, this proves the effectiveness of the excitation of random component in the cutting force.
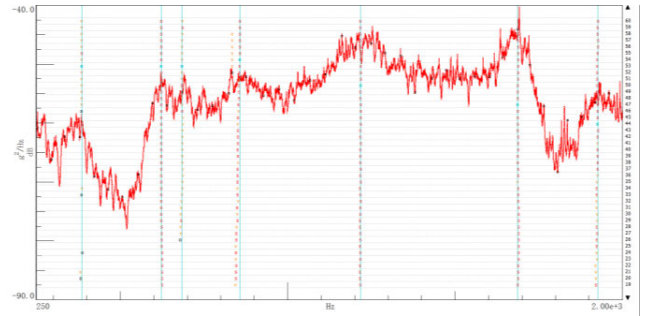

FIGURE 16. Mode stabilization diagram of the PSD after removing periodic components.

TABLE 3. Modal parameters of spindle head in X direction in impacting test and milling test.

Modes		1	2	3	4	5	6	7
Impacting Test	f(Hz)	361.12	613.12	687.80	899.07	1218.03	1677.22	1903.24
	ζ(%)	7.40	2.81	2.45	2.41	5.20	1.69	1.48
Milling Test	f(Hz)	385.40	622.76	684.83	857.19	1218.18	1687.21	1926.44
	ζ(%)	0.16	3.77	0.35	2.933	4.24	0.88	0.71

2) PERIODIC COMPONENT ELIMINATION AND PARAMETER IDENTIFICATION

The real cepstrum of the spindle head acceleration signal is shown in Figure 14a. It can be seen that the amplitude of discrete pulses with a period of 1/20s (corresponding to the spindle frequency of 20 Hz) is particularly high, and there are also discrete pulses with a period of 1/80s (corresponding to the tooth passing frequency of 80Hz).

To remove periodic components in the signal, the period of the notch filter function is set to 1/80s ($T = 1/80s$), the value of $\Delta\tau$ is set to 16% of T ($\Delta\tau = 1/500s$), the value of τ_p is 0.01s. Figure 14b shows the edited real cepstrum. The periodically forced vibration component in the higher quefrency band is eliminated after multiplying the real cepstrum by the notch filter function.

The acceleration signal after cepstrum editing is shown in Figure 15a. Compared with the original acceleration signal, the periodic component in the signal is well eliminated after cepstrum editing, and the random component in the signal is remained. The PSD within 2000Hz of the acceleration signal after removing the periodic component is shown in Figure 15b. It can be found that the harmonics in the original PSD are well eliminated.

The Op. PolyMAX algorithm in LMS.Test.Lab was used to identify the parameters from the PSD after removing the periodic components. The mode stabilization diagram is shown in Figure 16. It can be seen that without the interference from harmonics, clear pole queues appear at various modal frequencies.

The identified modal parameters are shown in Table 3. It can be found that the natural frequencies and damping ratios of the machine tool in the cutting state have changed to a certain extent relative to the static state. In particular, the damping ratios change greatly.

IV. CONCLUSIONS

This paper proposes a method for identifying modal parameters of machine tools under normal machining conditions. Based on the characteristics of the cutting force generated during machining, the random component in the cutting force can supply broadband random excitation to the machine tool. However, due to the strong periodic component, the cutting force excitation does not satisfy the white noise assumption, so that the OMA method cannot be directly applied to identify modal parameters from the original vibration signal.

In this research, the cepstrum editing method was used to eliminate periodic component in the vibration signal by applying a notch filter to the real cepstrum. Then, the random component was obtained to identify parameters with the OMA method. The result in a normal periodic cutting experiment validates the effectiveness of the method.

REFERENCES

[1] S. Seguy, F. J. Campa, L. N. L. de Lacalle, L. Arnaud, G. Dessein, and G. Aramendi, "Tool path dependent stability lobes for the milling of thin-walled parts," *Int. J. Machining Machinability Mater.*, vol. 4, no. 4, pp. 377–392, 2008.

[2] F. I. Compeán, D. Olvera, F. J. Campa, L. N. López De Lacalle, A. Elías-Zñiga, and C. A. Rodríguez, "Characterization and stability analysis of a multivariable milling tool by the enhanced multistage homotopy perturbation method," *Int. J. Mach. Tools Manuf.*, vol. 57, pp. 27–33, Jun. 2012.

[3] G. Urbikain, L. N. López De Lacalle, F. J. Campa, A. Fernández, and A. Elías, "Stability prediction in straight turning of a flexible workpiece by collocation method," *Int. J. Mach. Tools Manuf.*, vols. 54–55, pp. 73–81, Mar. 2012.

[4] G. Urbikain, F.-J. Campa, J.-J. Zulaika, L.-N. López De Lacalle, M.-A. Alonso, and V. Collado, "Preventing chatter vibrations in heavy-duty turning operations in large horizontal lathes," *J. Sound Vib.*, vol. 340, pp. 317–330, Mar. 2015.

[5] N. Tounsi and A. Otho, "Identification of machine–tool–workpiece system dynamics," *Int. J. Mach. Tools Manuf.*, vol. 40, no. 9, pp. 1367–1384, Jul. 2000.

[6] O. Özäahin, E. Budak, and H. N. Özgäven, "Investigating dynamics of machine tool spindles under operational conditions," *Adv. Mater. Res.*, vol. 223, pp. 610–621, Apr. 2011.

[7] B. Li, H. Cai, X. Mao, J. Huang, and B. Luo, "Estimation of CNC machine–tool dynamic parameters based on random cutting excitation through operational modal analysis," *Int. J. Mach. Tools Manuf.*, vol. 71, pp. 26–40, Aug. 2013.

[8] A. Iglesias, J. Munoa, C. Ramírez, J. Ciurana, and Z. Dombovari, "FRF estimation through sweep milling force excitation (SMFE)," *Procedia CIRP*, vol. 46, pp. 504–507, Oct. 2016.

[9] B. Li, B. Luo, X. Mao, H. Cai, F. Peng, and H. Liu, "A new approach to identifying the dynamic behavior of CNC machine tools with respect to different worktable feed speeds," *Int. J. Mach. Tools Manuf.*, vol. 72, pp. 73–84, Sep. 2013.

[10] X. Mao, B. Luo, B. Li, H. Cai, H. Liu, and F. Pen, "An approach for measuring the FRF of machine tool structure without knowing any input force," *Int. J. Mach. Tools Manuf.*, vol. 86, pp. 62–67, Nov. 2014.

[11] B. Luo, D. Pan, H. Cai, X. Mao, F. Peng, and K. Mao, "A method to predict position-dependent structural natural frequencies of machine tool," *Int. J. Mach. Tools Manuf.*, vol. 92, pp. 72–84, Oct. 2015.

[12] X. Liu, X. Mao, H. Liu, B. Li, C. Guan, Z. Zhang, B. Luo, and F. Peng, "Method for identifying feed-drive system dynamic properties using a motor current," *Int. J. Mach. Tools Manuf.*, vol. 110, pp. 92–99, Nov. 2016.

[13] I. Zaghbani and V. Songmene, "Estimation of machine-tool dynamic parameters during machining operation through operational modal analysis," *Int. J. Mach. Tools Manuf.*, vol. 49, nos. 12–13, pp. 947–957, Oct. 2009.

[14] T. Österlind, C. Frangoudis, and A. A., "Operational modal analysis during milling of work piece, fixed on a stiffness controllable joint," *J. Mach. Eng.*, vol. 13, pp. 69–78, Apr. 2013.

[15] A. W. Kwiatkowski and H. M. Al-Samarai, "Identification of milling machine receptances from random signals during cutting," *Ann. CIRP*, vol. 16, pp. 137–144, Jan. 1968.

[16] R. B. Randall and S. N., "Use of the cepstrum to remove selected discrete frequency components from a time signal. Rotating Machinery," *Rotating Mach., Struct. Health Monitor., Shock Vib.*, vol. 5, pp. 451–461, Dec. 2011.

[17] R. B. Randall, M. D. Coats, and W. A. Smith, "OMA in the presence of variable speed harmonic orders," in *Proc. Int. Conf. Struct. Eng. Dyn.*, 2015, pp. 22–24.

[18] R. B. Randall, M. D. Coats, and W. A. Smith, "Repressing the effects of variable speed harmonic orders in operational modal analysis," *Mech. Syst. Signal Process.*, vol. 79, pp. 3–15, Oct. 2016.

[19] B. Peeters, B. Cornelis, K. Janssens, and H. V. D. Auweraer, "Removing disturbing harmonics in operational modal analysis," Tech. Rep., 2007.

[20] W. D. Mark, "Time-synchronous-averaging of gear-meshing-vibration transducer responses for elimination of harmonic contributions from the mating gear and the gear pair," *Mech. Syst. Signal Process.*, vols. 62–63, pp. 21–29, Oct. 2015.

LING YIN received the Ph.D. degree in mechanical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2011.

She is currently an Associate Professor with the School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China. Her research interests include numerical control technology and intelligent equipment condition monitoring for big data applications.

CHUNHUI LI was born in Tangshan, China, in 1996. He received the bachelor's degree in logistics engineering from the Wuhan University of Technology, Wuhan, China, in 2018, and the master's degree in mechanical science and engineering from the Huazhong University of Science and Technology, Wuhan.

His research interests include machine tool dynamics, machine learning, and mechanical metrology calibration.

CHAO QIN was born in Huanggang, China, in 1994. He received the bachelor's degree in mechanical engineering from the Nanjing University of Science and Technology, Nanjing, China, in 2015, and the master's degree in mechanical science and engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2018.

His research interests include machine tool dynamics, cutting excitation, and modal parameter identification.

YILI PENG was born in Luoyang, China, in 1987. She received the B.S. and M.S. degrees in energy and power engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2009 and 2012, respectively, where she is currently pursuing the Ph.D. degree in mechanical science and engineering.

From 2012 to 2015, she was an Engineer in structural design at Harbin Electric Machinery Company Ltd. Her research interests include structural dynamics, modal analysis method, and intelligent manufacturing. Her awards and honors include the academic scholarship from the Huazhong University of Science and Technology.

SHUO LI was born in Chaozhou, China, in 1996. He received the B.S. degree from the School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China, in 2018. He is currently pursuing the M.S. degree with the School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, China.

His research interests include machine learning and data analysis.

JIARONG GU was born in Wuhu, China. He received the bachelor's degree in mechanical engineering from the Nanjing University of Aeronautics and Astronautics, in 2018. He is currently pursuing the master's degree with the CNC Center, Huazhong University of Science and Technology.

His research interests include machine tool dynamics, group machine tools, and fault diagnosis.

FEI ZHANG received the Ph.D. degree in mechanical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2017.

His research interests include digital design and Industry 4.0.

ZHIQIANG SONG was born in Linyi, China, in 1987. He received the master's degree in aerospace engineering from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2013. His current research work is mechanical metrology calibration.

• • •