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

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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 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 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.
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 stationary 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 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:

\[ C_c(\tau) = F^{-1}\{\ln[F(f)]\} = F^{-1}\{\ln[A(f)] + j\phi(f)\} \quad (2.1) \]
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:

$$Y(f) = F(f) \cdot P(f) = A_f(f)e^{j\phi_f(f)} \cdot A_p(f)e^{j\phi_p(f)}$$

$$= [A_f(f) \cdot A_p(f)] \cdot [e^{j\phi_f(f)} \cdot e^{j\phi_p(f)}]$$

$$= [A_f(f) \cdot A_p(f)]e^{j[\phi_f(f)+\phi_p(f)]} \quad (2.5)$$

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:

$$C_{cy}(\tau) = F^{-1} \{ \ln |Y(f)| \}$$

$$= F^{-1} \{ \ln |F(f) \cdot P(f)| \}$$

$$= F^{-1} \{ \ln |F(f)| + \ln |P(f)| \}$$

$$= F^{-1} \{ \ln |F(f)| \} + F^{-1} \{ \ln |P(f)| \}$$

$$= C_{cf}(\tau) + C_{cp}(\tau) \quad (2.6)$$

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):

$$C_{ry}(\tau) = F^{-1} \{ \ln |Y(f)| \}$$

$$= F^{-1} \{ \ln |A_f(f) \cdot A_p(f)| \}$$

$$= F^{-1} \{ \ln |A_f(f)| + \ln |A_p(f)| \}$$

$$= F^{-1} \{ \ln |A_f(f)| \} + F^{-1} \{ \ln |A_p(f)| \}$$

$$= C_{cf}(\tau) + C_{cp}(\tau) \quad (2.7)$$

where $C_{cf}(\tau), C_{cp}(\tau)$ 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.
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:

\[
C_{r,\text{edited}}(\tau) = q(\tau) \cdot C_r(\tau) \tag{2.8}
\]

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 \( \tau_p \) is used to improve the notch filter. When \( \tau \leq \tau_p \), the value of \( q(\tau) \) is always 1. The value of \( \tau_p \) 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.

TABLE 1. Experimental conditions.

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

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, \( \pm 50 \) g; frequency range (\( \pm 5\% \)), 0.5–5000 Hz; resonant frequency, \( \geq 25 \) 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,
±500 g; frequency range (±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, ± 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.

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 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
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.

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 $1\tau$ is set to 16% of $T$ ($1\tau = 1/500 s$), the value of $\tau_p$ 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.

| Modes | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-------|---|---|---|---|---|---|---|
| Impacting Test | $f(\text{Hz})$ | 361 | 613 | 687 | 899 | 121 | 167 | 190 |
|            | $\zeta(\%)$ | 7.4 | 2.8 | 2.4 | 2.4 | 5.2 | 1.6 | 1.4 |
| Milling Test | $f(\text{Hz})$ | 385 | 622 | 684 | 857 | 121 | 168 | 192 |
|            | $\zeta(\%)$ | 0.1 | 3.7 | 0.3 | 2.9 | 4.2 | 0.8 | 0.7 |

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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.

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