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The Effect of the Low Frequency Mode of the Machine Tool Structure on the Milled Surface Generation

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Abstract: The prediction of machining process stability and surface generation is primarily based on the dynamics of the tool and work piece. However, the vibrations caused by the low frequency of machine tool structure also affect the stability of machining process and the surface integrity in the condition of low speed and heavy load. Therefore, this paper presents a milling time domain simulation model based on the low frequency mode of machine tool structure to study the effect of the low frequency mode of the machine tool structure on the surface generation. Based on this model, the correlation between the multimode natural frequencies of machine tool structure and the surface waviness is studied and the effect of the inertia force caused by the change of cutting speed on the surface shape is studied. Finally, a set of cutting tests is performed to verify the surface generation prediction.

1. Introduction
The milled surface topography could be predicted through the time domain simulation of the machining process. The accurate prediction of surface generation is beneficial to the optimization of processing parameters. Montgomery et al. [1] proposed the model of the mechanics and kinematics of dynamic milling to predict the cutting force and the topology of a finished work piece surface. Campoanes et al. [2] presented an improved time domain simulation model for small radial immersions. Paris et al. [3] presented a machined surface generation model for high speed milling and studied the effect of machining parameters on the surface shape and roughness of the machined surface. Eksioglu et al. [4] presented a discrete time modeling of dynamic milling system that could be used for variable pitch and helix angles to predict the surface location errors, chatter stability and cutting forces. Yang et al. [5] studied the surface generation mechanism in peripheral milling with variable pitch end mills and predicted the surface topography considering the machining error sources from tilting, run-out and the deflection of the tool and work piece displacement. Kiran et al. [6] presented a two degree-of-freedom frequency-domain solution for surface location error prediction.

To predict the surface shape accurately, the study of the relationship of vibration during cutting and dynamics of machine tool and the surface integrity is significant and meaningful. de Aguiar MM et al. [7] studied the correlation between the frequency response function and both the tool wear and workpiece surface roughness. The research indicated that high amplitude vibrations occur when the harmonics of tooth passing frequencies are close to the system’s natural frequency. Good workpiece surface roughness related to long tool life of long slender tools can be achieved provided that the tooth passing frequency used does not produce high frequency response function values. Peigne et al. [8] studied the impacts of cutting vibration on the roughness of the machined surface and reported a different
finding, claiming that during the stable cutting, the forced vibrations have only a very slight impact, and the unstable cutting primarily impacts roughness. Shimana et al. [9] studied the relationship between the vibration displacement and the machining error and observed that the machining error caused by the deflection of the tool at the cutting point in end-milling processes at a spindle speed of 1000rpm could be closely estimated from the static stiffness of the end mill system and the quasi-static cutting force but the machining error caused by the vibration must be considered with the increase of the spindle speed. Zhang et al. [10] studied the effect of the multimode high frequency vibration on the surface generation in ultra-precision diamond turning. Schmitz et al. [11] experimentally quantified the relative contributions of geometric, thermal, contouring, and cutting force errors to the machined part dimensional errors and observed that the cutting force error contribution is greater than the combined effect of the other error sources for certain choices of spindle speeds but may become insignificant at slightly different spindle speeds.

The current prediction model was mainly based on the dynamics of the tool and the work piece. This model adapts the condition of high speed and light load, however, under the conditions of low speed and heavy load, the effect of the direction and position dependent dynamics of machine tool structure must be considered. Law et al. [12] studied the effect of the position dependent dynamics of machine tool structure on the machining stability. Kono et al. [13] studied the direction dependency of tool-workpiece compliance of machine tool and reported the large discrepancy of compliance in different directions in the frequency range lower than 250Hz; the direction dependency was small in the frequency range higher than 250Hz which was primarily from the spindle and tool. The current prediction model of surface topography and the study of the effect of vibration on the surface topography in the machining process only considered the vibration caused by the cutting force. The vibration caused by the inertia force due to the change of cutting speed was not considered. The research of Wang et al. [14] showed that the high acceleration and braking forces cause the elastic deformation and vibration of a machine tool.

This paper establishes a time domain simulation model considering the influence of the low frequency mode of machine tool structure and the inertia force to study the effect of the dynamics of the machine tool structure on the surface generation. The principle of the model is provided in Section 2. In Section 3, a simulation case is conducted and the link between the surface waviness and the dynamics of machine tool structure is analysed. Section 4 provides the experimental verification of the result of the simulation. Finally, the study’s conclusions is presented in Section 5.

2. Theoretical background

The prediction of machined surface generation could be realized through the time domain simulation of the machining process. The presented time domain simulation model is based on the model of “Cycloidal tool path, Regenerative Force, Dynamic Deflection Model” [15]. The effect of inertia force caused by the change of cutting speed is considered in the model of this paper.

2.1. Calculation of the vibration displacement caused by the inertia force

The inertia force caused by the cutting speed can be approximated by a rectangular wave.

\[ g(t) = \begin{cases} A_r, t \in [0, \tau] \\ 0, t \notin [0, \tau] \end{cases} \] (1)

The dynamic equations of the machine tool structure under the excitation of inertia force are as follows:

\[ m_{x,r} \ddot{u}_{x,r} + c_{x,r} \dot{u}_{x,r} + k_{x,r} u_{x,r} = g_x \] (2)

\[ m_{y,r} \ddot{u}_{y,r} + c_{y,r} \dot{u}_{y,r} + k_{y,r} u_{y,r} = g_y \] (3)

Where \( m_{x,r}, c_{x,r}, \) and \( k_{x,r} \) are the \( r \)-th order modal parameters in the \( x \) direction. \( r = 1, 2, \ldots, n \); \( u_{x,r} \) is the \( r \)-th order modal displacement in the \( x \) direction; \( g_x \) is the inertia force in the \( x \) direction. \( m_{y,r} \).
$c_{y,r} \cdot k_{y,r} \cdot y_{y,r}$ and $g_y$ are the corresponding parameters in the y direction. The total displacement caused by the inertia force is the sum of the multiple modal displacements.

$$x_i = \sum_{r=1}^{n} u_x(r) \cdot y_i = \sum_{r=1}^{n} u_y(r)$$  \hspace{1cm} (4)

2.2. Calculation of the vibration displacement caused by the cutting force

The instantaneous cutting force can be determined as follows:

$$F_{t,j} = k_t b h_j + k_n b$$  \hspace{1cm} (5)

$$F_{n,j} = k_n b h_j + k_{ne} b$$  \hspace{1cm} (6)

Where $F_{t,j}$ and $F_{n,j}$ are the tangential and normal force components, $k_t, k_n, k_{te}, k_{ne}$ are the tangential, normal, tangential edge, and normal edge cutting force coefficients. $b$ is the axial depth of cut, and $h_j$ is the instantaneous chip thickness. The cutting force in the x and y directions can be calculated through the projections of $F_{t,j}$ and $F_{n,j}$. The vibration displacement caused by the cutting force can also be calculated through the modal displacement equations.

3. Simulation of the surface prediction

The simulator is coded using MATLAB, the tangential cutting force coefficient is 771.2 N/mm$^2$, and the normal cutting force coefficient is 254.5 N/mm$^2$. The modal parameters of the machine tool structure are provided in Section 3.1, and the other input parameters are listed in Table 1.

| number of teeth | tool diameter (mm) | helix angle (°) | spindle speed (r/min) | feed speed (mm/min) | axis depth of cut (mm) | radial depth of cut (mm) |
|-----------------|--------------------|----------------|-----------------------|---------------------|-----------------------|------------------------|
| 3               | 12                 | 35             | 3000                  | 1000                | 5                     | 0.1                    |

3.1. Dynamics of machine tool structure

The modal parameters of machine tool structure in x and y directions are obtained by impact testing. All of the tests in this paper are conducted in a 3-axis vertical machining center DM4600. A micro-accelerometer sensor (DYTRAN 3224A1) is attached to the tool. Seven accelerometers (PCB 356A16) are attached to the spindle head, the work table, the fixture and the work piece. Two hammers are used in this test: the PCB impulse hammer 086C03 is used to impact the tool point and the HDFC-DFC-1 hammer is used to impact the machine tool structure. Both the impact force of the hammers and the vibration responses of all the measurement points are recorded synchronously and then processed using the acquisition and analysis system LMS Test Lab. To reduce the test errors, the frequency response functions from five repeated tests are averaged.

The frequency response functions (FRF) obtained from the test are shown in Figure 1. Figure 1 (a) shows the FRF of the measurement point on the work table. Figure 1 (b) shows the FRF of the work piece. Figure 1 (c) shows the FRF of the spindle head. Figure 1 (d) shows the FRF of the tool. The dominant natural frequencies of the tool are 907 Hz in the x direction and 844 Hz in the y direction. The identified modal parameters of the machine tool structure are in the range of low frequency as listed in Table 2. The dominant natural frequencies of the machine tool structure in the x direction are 14.3 Hz and 45 Hz, and those in the y direction are 15.3 Hz and 54 Hz.
Figure 1. (a) FRF of the measurement point on the work table; (b) FRF of the work piece; (c) FRF of the spindle head; (d) FRF of the tool

Table 2. Modal parameters of machine tool structure

| Mode number | Natural frequency (Hz) | Damping ratio (%) |
|-------------|------------------------|-------------------|
| 1st mode in x direction | 14.3 | 3.31 |
| 2st mode in x direction | 36.9 | 2.35 |
| 3st mode in x direction | 45 | 1.17 |
| 4st mode in x direction | 56 | 3.1 |
| 5st mode in x direction | 60.4 | 4.25 |
| 1st mode in y direction | 15.3 | 3.3 |
| 2st mode in y direction | 30.4 | 2.1 |
| 3st mode in y direction | 45 | 4.62 |
| 4st mode in y direction | 54 | 4.95 |
| 5st mode in y direction | 65 | 6.96 |

3.2. Discussion of the simulation result

The surface prediction of a straight-line path machining in the y direction is shown in Figure 2. If the vibration was not considered in the simulation, i.e., the machining system was rigid, then the machined surface waviness was only caused by the feed motion of the tool. The surface shape is the envelope of all of the trochoids produced by the feed motion and the cutter rotation. The distance among the waviness
of the surface is equal to the feed per tooth (0.11mm) as shown in Figure 3. Comparing the surface shape considering the dynamics of machine tool as shown in Figure 2 and that without considering the vibration as shown in Figure 3, three types of geometric defects are observed.

Figure 2. Surface shape of a simulation for a straight-line path

Figure 3. Surface shape from the simulation without vibration

The first geometric defect is the effect of inertia force caused by the change of feed speed. The tool-workpiece is subjected to the inertia force and cutting force; therefore, the amplitude of vibration is larger than that without the excitation of inertia force. As shown in Figure 2, the amplitude of the beginning of the surface waviness is larger and the distance among the waviness is longer.

The second geometric defect is the effect of the dynamics of the structure on the peak-to-peak distance of the surface waviness. In the simulation of Figure 2, the tooth passing frequency is 150 Hz. The dominant natural frequencies in the x direction are 14.3 Hz and 45 Hz. The triple the frequency of 45 Hz is approximately the tooth passing frequency. The triple the feed rate per tooth of 0.11 mm is 0.33 mm, which is close to the average peak-to-peak distance of the surface waviness 0.34 mm as shown in Figure 2. The effect of the dominant natural frequency 14.3 Hz is not very clear in the surface shape shown in Figure 2, whereas in the FFT of the surface waviness as shown in Figure 4, the effect of the dominant natural frequency 14.3 Hz can be found.

The surface topography is the coupling of the waviness produced by the feed motion and the vibration caused by the low frequency dynamics. When the vibration amplitude caused by the dominant natural frequency is small, the waviness from the feed motion remains in the coupling waviness as shown in Figure 5. When the vibration amplitude caused by the dominant natural frequency is large, the waviness from the feed motion will be displaced by the vibration as shown in Figure 2.

The third geometric defect is the effect of the dynamics of the structure on the residual height and the roughness. The peak-to-peak surface roughness $R_t$ of the machined profile without considering the vibration can be determined as follows [8]: $R_t = f_{feed/tooth}^2 / 8R$, where $f_{feed/tooth}$ is the feed rate per
tooth, and R is the tool radius. The roughness obtained according this formula for the cutting parameter in this case is 0.252 \( \mu m \), and the roughness considering the vibration obtained through the simulation is 0.453 \( \mu m \).

Figure 4. FFT of the surface topography of the simulation

Figure 5. Simulation surface shape with small amplitude of vibration

4. Experimental verification
To verify the accuracy of the model for surface prediction, a set of cutting tests was performed in a 3-axis vertical machining center DM4600. The work piece material is aluminum, and the cross-section of the work piece is square to ensure the same dynamics of the x and y directions. The tool geometry and the cutting parameters are the same as that in the simulation case as shown in Table 1. The PGI-830 comprehensive measurement system for surface profile by Taylor Hopson Limited is used to characterize the machined surfaces. The results of the measurements are shown in Figure 6. A comparison of the simulation and experiment results is presented in Table 3. The peak-to-peak distances of the surface waviness of the experiment are in agreement with the results of simulation, as shown in Table 3. The amplitudes of the surface waviness of the experiment are slightly larger than the prediction, resulting in the smaller values of the prediction of roughness compared to the actual values. The effect of the inertia force is also observed in the surface profile of machined work piece. The model based on the low frequency mode of the machine tool structure provides good predictions of the trend of the machined surface.

| Test(mm) | Simulation(mm) | Test(um) | Simulation(um) |
|----------|---------------|----------|----------------|
| 0.34     | 0.34          | 0.68     | 0.45           |
5. Conclusions
A simulation model based on the low frequency mode of machine tool structure to predict the surface profile was presented in this paper. This model considered the effect of the inertia force caused by the change of feed speed and the dynamics of machine tool structure. This simulation result was verified by a set of cutting tests and was consistent with the result of the tests.

The correlation of the dominant natural frequency of machine tool structure and the surface waviness was studied in this paper. According to the results, the surface shape is the coupling of the waviness produced by the feed motion and the vibration. When the vibration amplitude caused by the dominant natural frequency of machine tool structure is large, the roughness and the distance of peak to peak of the surface waviness are primarily determined by the vibration. When the vibration amplitude caused by the dominant natural frequency is small, the roughness is influenced by both the waviness left by the feed motion and the vibration. The effect of the inertia force on the surface topography was also studied and in the range of existing the excitation of inertia force, the amplitude of the surface waviness and the peak-to-peak distance is larger.

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Figure 6. Surface profile of the machined work piece