Surface roughness computer simulation in machining process

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Abstract

The present study is initiated to develop a generalized computer based simulation for predicting surface roughness for any given conditions which takes into consideration the important parameters influencing the dynamic behavior of the machine-tool-workpiece system. The parameters considered in the simulation are: machining variables, tool and workpiece variables, and machine-tool-workpiece system. Matlab Simulink™ is used to interactively perform the simulation in a user-friendly, effective and efficient manner. The effects of machining variables and tooling characteristics on the surface generation are investigated through simulations. Turning trials have been carried out to evaluate and validate the presented approach and simulations. Using simulation program, the results agreed with the cutting test in the prediction of the cutting process. The percentage errors between predicted and measured roughness parameters were found to be less than 20%. The method can be used to facilitate the planning of cutting parameters and optimization of tool geometry.

Keywords: Surface roughness, vibration, turning, computer simulation

1. Introduction

Surface finish is a factor of great importance in the evaluation of workshop production and considerable attention is now being focused on those measurements as a means of quality control. Such information can be used to assist in understanding critical machining attributes such as machinability, tool wear/fracture, machine tool chatter, machining accuracy and surface finish [1-2]. The capability of modeling cutting forces therefore provides an analytical basis for machining process planning, machine tool design, cutter geometry optimization, and online monitoring/control. The produced surfaces of machined components consist of two superimposed profiles; theoretical profile due to operation kinematics; and random profile due to cutting edge vibrations [1]. Many researchers developed a computer-based simulation to predict surface roughness [2-3] and to construct the topography of the machined surface [4-6]. The surface topography simulation model incorporated the effects of the relative motion between the cutting tool and the workpiece with the effects of tool geometry to simulate the resultant surface geometry. A cutting models, which contains a vibration cutting process, were proposed [7-8] to exhibit chatter suppression and work displacement.

Therefore, the present work aims to build an easy-to-use graphical user interface program capable of predicting surface roughness by integrating a dynamic cutting force model, regenerative vibration model, machining system response model and tool profile model.

2. Surface generation methodology

Figure 1 represents the basic elements of surface generation methodology developed in the present work to study the mechanism of the dynamic generation of the machined surface profile. The methodology uses the tool vibration response and the spiral trajectory of tool geometrical motion to generate the surface profile. Figure 2 shows a three system components
which are considered to have the major influence on the machining process which are: spindle structure, workpiece and tool dynamic characteristics, and the cutting forces [2].

The proposed dynamic model of the system deals only with transverse movements while the axial movement is assumed to be negligible. The spindle structure is defined by $M_s$, $C_s$ and $K_s$, the workpiece is defined by $M_w$, $C_w$ and $K_w$ and the tool is defined by $M_t$, $C_t$ and $K_t$. The system response is defined by $x_t$, $x_s$ and $x_w$. The equations of motion can be written as:

$$M_j \ddot{x}_j(t) + C_j \dot{x}_j(t) + K_j x_j(t) = F(t)$$  \hspace{1cm} (1)
$$M_c \ddot{x}_w(t) + C_w \dot{x}_w(t) - S_c x(t) = F(t)$$ \hspace{1cm} (2)
$$M_t \ddot{x}_t(t) + C_t \dot{x}_t(t) - C_w (x_w(t) - x_s(t)) = 0$$ \hspace{1cm} (3)

where $M_j$, $K_j$, $C_j$ is the dynamic characteristics of spindle structure, $M_w$, $K_w$, $C_w$ is the dynamic characteristics of tool structure and $M_w$, $K_w$, $C_w$ is the dynamic characteristics of workpiece.

The cutting force under steady state conditions can be reasonably considered to be directly proportional to the uncut chip cross-sectional area [9-12]. The equation of cutting force can be written as:

$$F_j = K_c K_r K_m K_{w} K_{cl} A_j \hspace{1cm} (j = 1, 2, \ldots, m)$$ \hspace{1cm} (4)

where $F_j$ is the dynamic cutting force at the $j^{th}$ tool mark and $K_c$, $K_m$, $K_{cl}$, $K_w$, $K_{cl}$, $K_v$ is the specific cutting resistance, coolant, tool material, cutting speed, tool wear and side rake angle correction factors, respectively.

The center of tool nose radius coordinates can be evaluated as a function of feed, tool nose radius, cutting speed and depth of cut as:

$$C_{ij} = \begin{cases} 0.1 f & j = 1 \\ 0.1 f + \frac{f_s s \delta}{60} & 1 > j \geq m \end{cases}$$ \hspace{1cm} and \hspace{1cm} $$C_{ij} = \begin{cases} d_j - r & j = 1 \\ C_{ij} & 1 > j \geq m \end{cases}$$ \hspace{1cm} (5)

$C_{ij}$ is the tool nose center points at $j^{th}$ tool mark and $f$, $s$, $d_i$ feed, cutting speed and depth of cut, respectively.

Surface profile generation considers the tool geometry and effect of tool spiral motion. The surface profile can be calculated as the maximum height of the resulting tool marks as:

$$Z_t = \max (Z_{cl}, Z_{p1})$$ \hspace{1cm} (6)
and the cross-sectional area, Fig. 3, for each turn can be calculated as the difference of current sum of areas and the previous sum of areas, as:

$$A_j = \sum_{i=1}^{n} Z_i - \sum_{i=1}^{n} Z_{i-1}$$  \hspace{1cm} \text{(7)}

where $A_j$ is the instantaneous chip area and $Z_i$ is the resulting z-coordinate of the workpiece surface.

3. Simulation software

Simulation software named Surface Generation Model, SurfGM, was purposely built for the implementation of the surface profile simulation model. The software was developed using MATLAB™. The SurfGM consists of three modules: data input module, preview and simulation module and roughness parameters calculation module. Data input module, Fig. 4, is built for easy to edit and to change machining variables, tool variables, workpiece variables and machine-tool-workpiece structural variables. It is possible to simulate surface profile in case of both ideal surfaces and the generated surfaces based on random and dynamic machine tool vibrations.

The second module is the surface profile preview, SurfPreview, which was build to preview the generated surface profile according to the input data, Fig. 5. The lower graph shows the resulting surface profile after applying least square mean line. The upper and lower graphs are updated according to simulation method selections. The ideal surface is the resulting profile due to feed and tool nose radius. The random vibration generates a profile that depends on a random tool vibration. The dynamic pushbutton uses the machine-tool-workpiece simulation to generate the predicted surface profile. The roughness parameters of the executed profile can be calculated by clicking the Done button, which displays the third module as shown in Fig. 6. The third module is the surface roughness parameters, SurfRP, which was built to display surface profile, bearing area curve, amplitude density curve, slope curve, number of intersection curve, high spot count curve, mean spacing at the mean line curve and the calculated roughness parameters. The calculated parameters are: Amplitude, spacing, hybrid and auxiliary surface roughness parameters.

Figure 7 shows the Matlab Simulink™ of the dynamic model of the proposed system. The main Simulink model, Fig. 7(a), draws a simulation of Eqs. 2 and 3 which represent the
dynamics of workpiece and spindle, respectively. A subsystem simulink model, Fig. 7(b), represents the simulation of Eq. 1 and the calculation of cross-sectional area of the chip.

![Simulink Models](attachment:fig7.png)

(a) Main Simulink model
(b) Subsystem Simulink model

Fig. 7. Matlab Simulink model of the dynam ic system.

4. Experimental verification

To verify the surface generation modeling of dynamic cutting process and tool geometry, a series of turning experiments for various cutting configurations and process parameters were performed using a turning machine. Surface roughness was measured and two-dimensional roughness parameters were calculated. The average of three measurements was calculated for both predicted and measured roughness.

A throwaway cemented carbide inserts were used in the experiment. The inserts have a tool nose radius of 0.4 mm and a side cutting edge angle of $\chi = 45^\circ$. The workpiece material was free cutting steel. The depth of cut was chosen to be 0.5 mm in the experiments. The used cutting conditions were selected at two levels for both feed (0.05 and 0.2 mm/rev) and rotational speed (355 and 710 rev/min).

Figure 8 shows a comparison of the predicted and measured surface roughness for cutting tests for workpiece diameter = 36 mm. It is obvious that the predicted surface profile is closely matched by that of the measured ones. Table 1 lists the means of the predicted and measured roughness parameters and its percentage errors. Percentage errors are calculated from the percentage of the prediction errors divided by the mean of measured roughness parameters. The maximum percentage prediction error is found to be less than 20% for all cases.

![Surface Profiles](attachment:fig8.png)

(a) Feed = 0.05 mm/rev and rotational speed = 355 rev/min
(b) Feed = 0.20 mm/rev and rotational speed = 355 rev/min

Fig. 8. Predicted and measured surface profile.
A Simulink model was built to solve the differential equation governing the dynamics of turning system for accurate solutions. Turning experiments under a wide range of cutting conditions were performed and results were presented in the verification of the analytical model. Comparisons between the simulated and experimental results have been presented to verify the dynamic model. It was shown that by using the proposed SurfGM program, the simulation results agreed to a certain extent with the cutting test in the prediction of the cutting process. The percentage errors between predicted and measured roughness parameters were found to be less than 20%. The method can be used to facilitate the planning of cutting parameters, optimization of tool geometry and on-line diagnostics.

5. Conclusion

In this paper, a predictive surface roughness model was presented for the simulation and analysis of the dynamic cutting process in turning based on workpiece material properties, the tool geometry, the cutting conditions and machine-tool-workpiece structure. The instantaneous undeformed chip thickness was modeled to include the dynamic modulations caused by the tool vibrations so that the dynamic regeneration effect was taken into account. A Simulink model was built to solve the differential equation governing the dynamics of turning system for accurate solutions. Turning experiments under a wide range of cutting conditions were performed and results were presented in the verification of the analytical model. Comparisons between the simulated and experimental results have been presented to verify the dynamic model. It was shown that by using the proposed SurfGM program, the simulation results agreed to a certain extent with the cutting test in the prediction of the cutting process. The percentage errors between predicted and measured roughness parameters were found to be less than 20%. The method can be used to facilitate the planning of cutting parameters, optimization of tool geometry and on-line diagnostics.

Table 1. Predicted and measured surface roughness parameters and their percentage errors.

<table>
<thead>
<tr>
<th>Roughness parameter</th>
<th>Rotational speed = 355 rev/min</th>
<th>Rotational speed = 710 rev/min</th>
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<tr>
<td></td>
<td>Feed = 0.05 mm/rev</td>
<td>Feed = 0.20 mm/rev</td>
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<tr>
<td></td>
<td>Mean of predicted roughness</td>
<td>Mean of measured roughness</td>
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<tr>
<td>$R_a$</td>
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References