SIMULATION AND CONTROL OF CUTTING FORCES IN 2-1/2 DIMENSIONAL END MILLING PROCESSES

Soichi Ibaraki, Masahiro Sakahira, Atsushi Matsubara, and Yoshiaki Kakino
Department of Precision Engineering, Kyoto University, Kyoto, 606-8501, JAPAN
E-mail: `ibaraki@prec.kyoto-u.ac.jp`

Abstract This paper presents a machining process simulator for 2-1/2 dimensional end milling processes. From an arbitrary NC program, the simulator extracts machining conditions that are not explicitly written in the NC program, such as the depth of cut, along the entire tool path. The cutting force is then simulated over the whole path based on the prediction model, which can be easily identified by conducting a set of pre-process machining tests. Furthermore, the process simulation can be straightforwardly extended to the cutting force control. An iterative learning control method of cutting forces based on in-process updating of the simulation model is presented. The validity of the process simulation and the cutting force control method is verified in experimentation.
Key Words End milling, cutting forces, machining process simulator, cutting force control

1 INTRODUCTION

In today's manufacturing industry, the potential of high-speed, high-acceleration machining centers is not fully utilized in most cases. In order to optimize the productivity while meeting the requirement for machining accuracies, the optimal process planning is a critical issue. In today's industry, the process planning relies to a high extent on expert machine operators' experience and knowledge. For safer, higher speed, and higher productive machining, our group has been developing the Intelligent Machine Tool [1] for the automated process planning and the on-line adaptation of machining conditions.

As one of key features of the Intelligent Machine Tool, this paper presents simulation and control methodologies of cutting forces in end milling processes. In end milling operations, the design of machining conditions, as well as that of the tool path, is a critical issue to optimize the productivity without sacrificing the tool life. By using the process simulation, the process planner can evaluate the optimality of the program with respect to the productivity, and the tool damage. Such a simulation is often found useful in various stages of machining [2]: 1) in pre-process: to evaluate and optimize cutting conditions and tool paths, 2) in process: to monitor the machining process, to detect the tool breakage and wear, 3) in post-process: to generate machining know-how database. Over the past years, there have been a considerable research works on the end milling process simulation (e.g. [2, 3, 4]). An advantage of the simulation model used in this paper is its simplicity, and its close tie to the cutting force control scheme. This paper also presents an iterative learning control method of cutting forces based on in-process updating of the simulation model.

2 PREDICTION MODEL OF CUTTING FORCES

Figure 1 depicts a schematic view of a two-dimensional end milling process on a straight path. In the figure, t_m and L respectively denote the maximum undeformed chip thickness and the arc

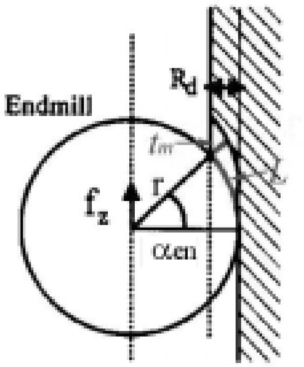


Fig. 1 Schematics of end milling process on a straight path

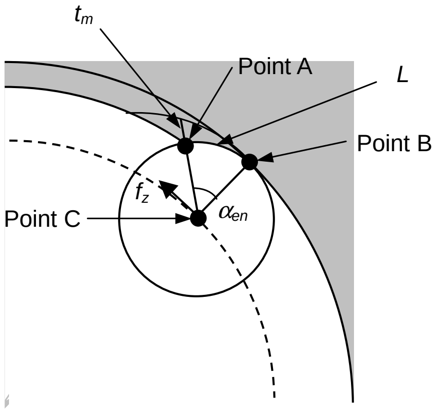


Fig. 2 Computation of t_m and L

length of cutting engagement. Based on the response surface methodology, Ohtsuka et al. [5] proposed a quadratic polynomial model to predict the cutting force by using these two variables:

$$\hat{F} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \tag{1}$$

where X_1 and X_2 respectively represent the variables, t_m and L, normalized by given central values. When six coefficients $(\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}, \beta_{12})$ in Eq. (1) are properly identified, its validity to predict the cutting force (either the tangential force, F_t, the normal force, F_n, or the combined force, $F_c = \sqrt{F_t^2 + F_n^2}$) has been verified by extensive experiments in [5].

3 EXTRACTION OF PROCESS PARAMETERS FROM CL DATA

To perform a numerical simulation of cutting forces by using the model (1), two parameters, t_m and L must be given along the entire path. A standard format NC program only provides a trajectory of the tool center. This section outlines an algorithm to extract a profile of t_m and L from arbitrary CL data for 2-1/2 dimensional milling operations. Note that the present algorithm can be seen as the simplification of geometric modeling algorithms for a general 3D swept volume (e.g. Wang et al. [6]).

To start the simulation, 1) a trajectory of the tool center, $((C_x(k), C_y(k)),\ k = 1, \cdots, N_c)$ (CL data), and 2) the initial geometry of workpiece surface on the same plane, $((B_x(k), B_y(k)),\ k = 1, \cdots, N_b)$, are assumed to be given. When the tool center is located at $(C_x(k), C_y(k))$ at time k, t_m and L can be computed as follows:

1. **The intersection of the tool and the workpiece surface (Point A)**
   The intersection of the tool and the workpiece surface (Point A in Figure 2), is first computed. If there exists no point among $(B_x(k), B_y(k))$ $(k = 1, \cdots, N_b)$ within the distance r from the tool center, then there is no interference between the tool and workpiece, i.e. it is an air cut. Otherwise, several points in $(B_x(k), B_y(k))$ $(k = 1, \cdots, N_b)$ are chosen from the nearest neighbor of the tool center, and their trajectory is curve-fit to a polynomial function. The location of Point A, denoted by $(A_x(k), A_y(k))$, can be computed as the intersection of this curve and a circle representing the tool surface.

2. **The point on the envelope surface (Point B)**
   Several points in $(C_x(k), C_y(k))$ $(k = 1, \cdots, N_b)$ are chosen from the nearest neighbor of the tool center, and their trajectory is curve-fit to a second-order polynomial function. By taking its derivative, the velocity vector at the tool center can be computed. The intersection of the tool surface and the envelope surface (Point B in Figure 2), denoted by $(B_x^0(k), B_y^0(k))$, can be computed such that this velocity vector and the vector from the tool center to Point B are perpendicular to each other.

3. **The engagement angle, α_{en}, and the arc length of cutting engagement, L**
   From the geometry shown in Figure 2, the engagement angle, α_{en}, and the arc length of cutting engagement, L, at time k, can be computed as follows:

$$\alpha_{en}(k) = 2\sin^{-1}\left(\frac{\sqrt{(A_x(k) - B_x^0(k))^2 + (A_y(k) - B_y(k))^2}}{2r}\right), \qquad L(k) = r\alpha_{en}(k) \qquad (2)$$

4. **The maximum undeformed chip thickness, t_m**
   From the geometry shown in Figure 2, the maximum undeformed chip thickness, t_m, at time k can be computed by:

$$f_z(k) = \frac{f(k)}{S \cdot n}, \qquad t_m(k) = f_z(k)\sin\alpha_{en}(k) \qquad (3)$$

   where $f(k)$: the feedrate at the tool center at time k (m/sec), which is given by the NC program, S: the spindle rotation speed (rev/sec), and n: the number of flutes of the tool, and $f_z(k)$: the feed per tooth at the tool center at time k (m/tooth).

5. **Updating the envelope surface**
   The points in $(B_x(k), B_y(k))$ $(k = 1, \cdots, N_b)$ that are within the distance r from the tool center are eliminated from the array. Point B, $(B_x^0(k), B_y^0(k))$, is added to the array $(B_x(k), B_y(k))$, which forms the "new" workpiece surface.

By repeating the above steps till the end of NC program, profiles of t_m and L can be simulated over the whole path.

4 CASE STUDIES

4.1 Experimental Conditions

The validity of the present machining process simulator is experimentally investigated on the machining of a rectangular pocket as an example. The geometry of the pocket is shown in Figure 3. The machining procedure is illustrated in Figure 4. First, the center hole of radius 10 mm is machined using a helical boring by an end mill. For the simplicity, this boring process is not considered in the following simulation and control experiments. Then, the hole is expanded by an end mill to a rectangular pocket as shown in Figure 4.

Experimental conditions are shown in Table 1. Throughout the experiments, a vertical-type medium-size machining center (VM4-II by OKK Corp.) was used. The cutting force was measured by using a dynamometer (Kistler Instrument Corp.'s 9272 piezoelectric four-component dynamometer) installed on the table.

4.2 Machining Process Simulation

In this experiment, the feedrate is constant at $f = 500$ mm/min over the whole path. First, the process simulation is performed in order to simulate the variation of cutting loads along this path, and to evaluate the possibility to further optimize the productivity. The coefficients of the prediction model (1) are provided from the database, which are identified based on pre-process machining tests using the same workpiece material and tool. Figure 5(a) shows the simulated profile of the cutting force on the X-Y plane. To validate this simulation result, an actual machining test was also performed under the same machining conditions. Figure 5(b) shows the measured cutting force profile. The validity of the process simulator is verified, although a slight error can be observed between the simulated and measured profiles,

When the feedrate is constant, the process (b) for example is subject to a large variation of the cutting force, since t_m and L continuously vary along the path. If the peaks are higher than the desired level, it should be reduced to avoid the tool damage and to extend the tool life. If the cutting force is lower than the desired level, the feedrate can be accelerated to shorten the total machining time. This observation motivates the implementation of the cutting force control to further enhance the productivity without sacrificing the tool life.

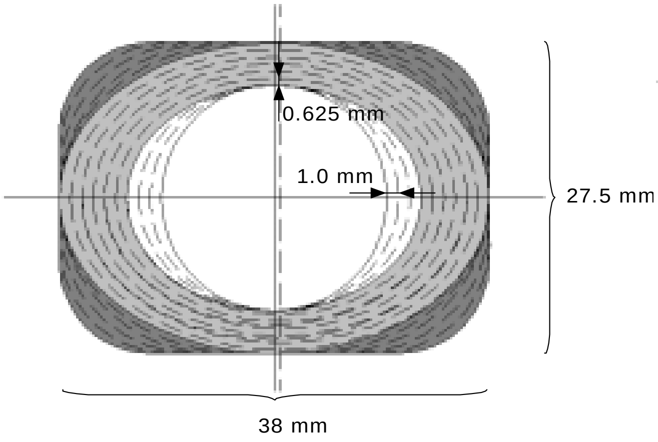


Fig. 3 Geometry of Pocket

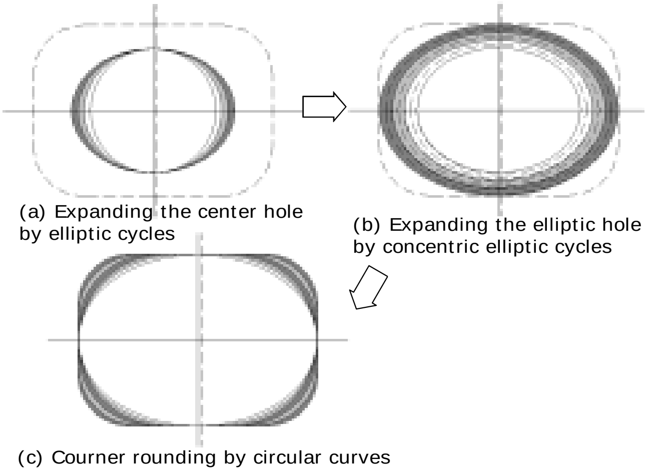


Fig. 4 Machining Procedure

Table 1 Experimental conditions

Tool	
Type/Material	Solid carbide end mill
Diameter	10 mm
Number of flutes	4
Tool Extension	35 mm
Axial Depth of Cut	5 mm

Workpiece	
Material	Carbon steel, S50C
Cutting conditions	
Spindle speed	2800 rpm
Milling method	Downcut
Coolant	Air blow

4.3 Model-based Learning Control of Cutting Forces

4.3.1 Control Scheme

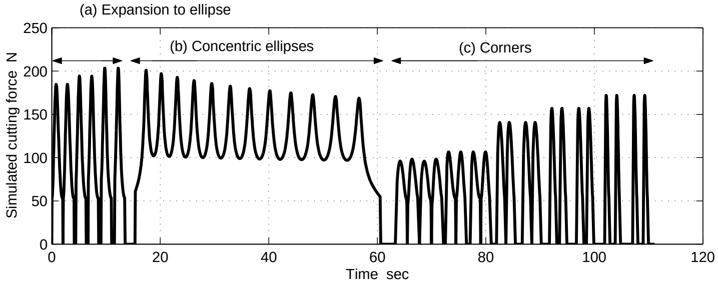
An advantage of the process simulation based on the model (1) is that it can be straightforwardly extended to the cutting force control. Ohtsuka et al. [5] presented a feedrate optimization methodology based on the model (1) such that the cutting force is regulated at given desired level over the whole path. When the desired cutting force level is given, the optimal feedrate profile can be computed by running the simulation presented in Section 3, and then solving Eqs. (1), (2) and (3) along the whole path.

Despite of its simplicity, this model-based feedforward control approach has an important advantage over feedback control approaches, where the feedrate is controlled on-line based on the feedback of measured cutting force (see [7] for further details). This paper employs the iterative learning control method proposed by Ibaraki et al. [7] based on this model-based control approach. Figure 6 illustrates a flow chart of the iterative learning control method. A feedrate profile at the first cycle is optimized based on the initial model, which is provided from the database. As machining cycles are iterated, the prediction model is updated at each cycle, and consequently, the control performance is improved in an iterative learning manner. The proposed learning scheme allows the model-based feedforward control approach to have the adaptability to unmodelled processes to some extent, which is an inherent advantage of feedback control approaches.

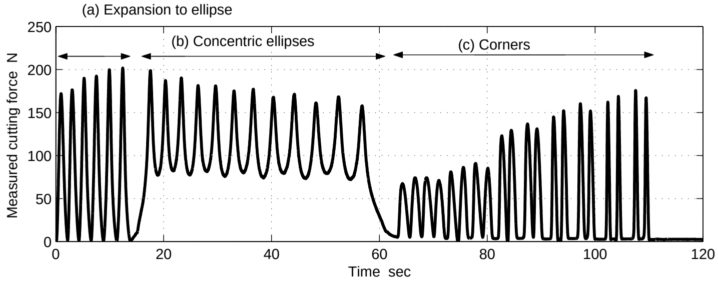
4.3.2 Experimental Results

The same pocket is machined with the iterative learning control system activated. The tool path and machining conditions are exactly the same as shown respectively in Figure 4 and Table 1.

Figure 7 shows a part of experimental results. Figure 7(a) shows the cutting force measured by a dynamometer in first three cycles in the process (a) of Figure 4. On the first cycle, the



(a) Simulated cutting force



(b) Measured cutting force

Fig. 5 Simulated and measured cutting force profiles over the entire process shown in Figure 4

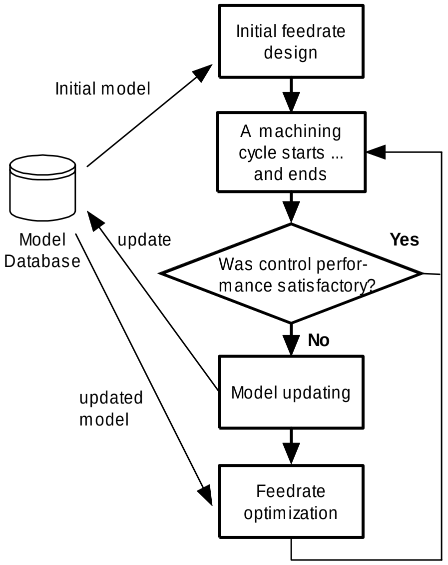
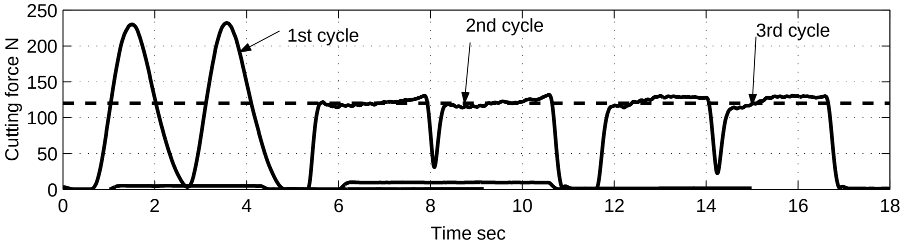


Fig. 6 Overview of model-based learning control algorithm [7]

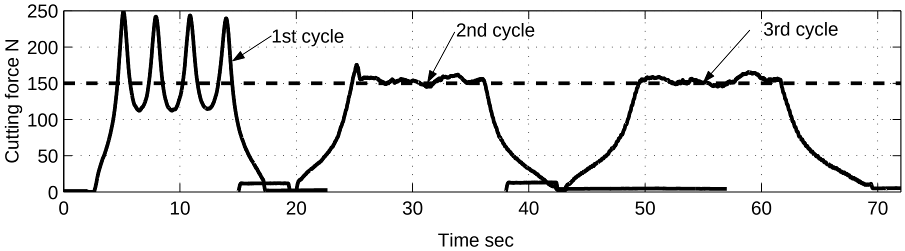
feedrate was fixed to 500 mm/min. The coefficients of the initial model (1) are updated based on the measurement of the cutting force over the first cycle. Then, the optimal feedrate is computed based on the updated model along the second cycle, such that the cutting force is regulated to the desired level, 150 N. The model updating and the feedrate re-computation are repeated at each cycle. Figure 7(a) shows that the error from the desired level was less that ±10 % at the second and third cycles. Note that in this experiment, each cycle was not machined continuously; after finishing each cycle, the machine was briefly stopped for the model updating and the feedrate re-computation, for a technical reason. Similarly, Figure 7(b) and (c) shows the measured cutting force on the first three cycles in the process (b) and (c) of Figure 4, respectively. In both cases, the feedrate on the initial cycle was fixed to 500 mm/min, and the feedrate optimization started from the second cycle. Experimental results show the effectiveness of the iterative learning control system in all of three cases, even when the exact cutting force prediction model is not given at the initial cycle.

5 Conclusion

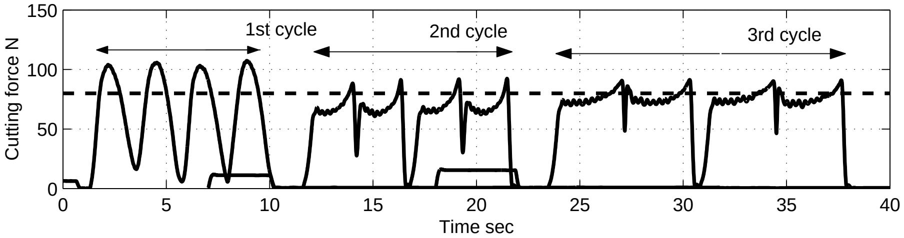
For the automation of machining process planning, the practical importance of the cutting force control has been widely recognized. This paper presented simulation and control methodologies of cutting forces in $2 - 1/2$ dimensional end milling processes as one of key features of the Intelligent Machine Tool. From an arbitrary NC program, the machining process simulator extracts machining conditions that are not explicitly written in the NC program. Then, the process simulation is performed over the whole path based on the prediction model of cutting forces. The process simulation can be easily extended to the process control. In this paper, an iterative learning control method of cutting forces based on in-process updating of the simulation model is presented. The validity of the process simulation and the cutting force control method was verified in experimentation, by taking the pocketing process as an example.



(a) Expanding the center hole to an elliptic hole (desired level=120N) (360° rotation defines one cycle)



(b) Expanding the elliptic hole (desired level=150N) (360° rotation defines one cycle)



(c) Corner rounding (desired level=80N) (each cycle machines four corners)

Fig. 7 Measured cutting force profiles with model-based learning control system activated

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