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Model-based feed rate optimization for cycle time reduction in milling

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Feed rate is an important determinant of cutting force and cycle time. Selection of appropriate feed rate can increase processing quality and production efficiency. Generally, in a software that generates tool path, the feed rate is determined based on the recommended conditions of the handbook provided by the tool company. Although various cutting conditions are included in one processing path, the recommended feed rate is limited to only one of slot milling or side milling. The optimal value of feed rate is derived based on the cutting force that depends on the cutting conditions, materials, and conditions of the equipment. For this reason, the limitedly recommended feed rate has low efficiency. To solve this problem, many methods were developed to maintain constant cutting force by applying real time feedback system. The feedback system was constructed with data such as tool condition, temperature and cutting load of spindle. However, these methods have low reliability, and a problem of different cycle time caused by changed feed rate in real time. In this study, the feed rate optimization that maintains cutting force was developed based on cutting force prediction model and an algorithm that extract cutting conditions from G code each line. The feed rate optimization is applied to flat end mill and ball end mill. The interpreter of G code were configured to calculate the tool center point and cutting condition. The real time spindle power measuring system were constructed to predict cutting force of G code for each line by identifying parameters of cutting force prediction model. The criteria cutting force was selected by highest value among the predicted cutting forces. The optimized feed rate that maintains the cutting force was extracted based on the cutting conditions of other lines and the cutting force prediction model. The extracted feed rate are applied to G code by modifying only feed rate command F. The feed rate optimized G code is newly generated. Experimental results by using commercial machine tool show that the proposed feed rate optimization significantly reduces overall cycle time and maintains the cutting force well.

NOMENCLATURE

F_t = Tangential cutting force
K_{tc}, K_{te}, k_1, k_2 = Cutting coefficient
h = Chip thickness
a = Depth of cut
ϕ = Instantaneous angle
ϕ_{st}, ϕ_{ex} = Cutting entry, exit angle
f = Feed per revolution
w = Width of cut
D = Tool diameter

1. Introduction

The feed rate is one of the most important determinant parameter to decide productivity and quality of product in the cutting process such as milling, turning, grinding, etc. In the milling process, the optimized feed rate lead to short cycle time and high precision. However, if the feed rate is set up too fast, the high cutting forces greatly accelerate tool wear and even generates breakage of the tool. On the other hand, if the feed rate is set up too slow, the cycle time is increased and decrease the production efficiency. Generally, when creating the G-code with tool path software, the feed rate is selected as the recommended condition based on the hand book of the tool company. However, the recommended condition is selected only one of groove cutting or side cutting, and the fixed feed rate is not changed until the end of the G-code in the tool path software. But, one usual cutting path contain various cutting conditions such as cutting entry angle, cutting exit angle, width of cut, etc. Moreover, it is difficult to know the optimal feed rate for materials not provided in the hand book. The optimal value of feed rate is abstracted based on cutting force that varied by cutting conditions, materials, conditions of equipment. For these reasons, the cutting force is changed by various conditions in one processing path, and the optimal feed rate to maintain the cutting force is also changed.

To solve this problem, the feed rate optimization is one of the most critical methods of CNC machine tools being developed toward high speed, high precision and high efficiency. For this purpose, many studies have been conducted. Yoram Koren summarized the area of adaptive control for machining process and improved the performance of the adaptive control system based on setting variables in real time system. The input data of adaptive algorithm was consisted with required force, spindle speed, and feed limits. Adaptive control routine calculate feed rate by input data. The feed rate was adjusted in real time in one path which the cutting depth was changed to maintain a constant cutting force [1]. These adaptive controls for machining have been applied to commercial CNC machining center since the 2000s. Omative and SIEMENS developed adaptive control based on tool monitoring system such as tool overload, tool breakage, no-load situations etc. Fanuc applied smart adaptive control based on data of cutting force and cutting temperature. Heidenhain used measured spindle load data of first cutting for adaptive feed control. All of these companies reduced cycle time and increased productivity by adaptive control based on real time data acquiring system. However, these real time based adaptive control has low reliability because of difficulty of abstract the correct cutting load and noise of measuring signals of cutting load. In addition, problem of irregular cycle time would be occurred because of varying feed rate in real time based on cutting conditions.

In this paper, a model based feed rate optimization in milling process is suggested. The cutting force model was composed of cutting conditions and cutting coefficient. The cutting force model was constructed by two types of flat end mill and ball end mill. The optimized feed rate was abstracted based on the cutting force model. The cutting load was maintained by adjusting the feed rate with the abstracted optimum value. As the feed rate increased, the cycle time decreased. A real-time spindle cutting load measurement system was constructed to increase the reliability of the cutting force model by comparing the measurement data and the estimated data. Also, by using this comparing system, the transition in machining center or processing condition such as tool wear, breakage and spindle condition can be predicted.

This paper is organized as follows. In Section 2, optimization algorithm such as cutting force model, cutting condition algorithm, spindle power measuring system, etc. Section 3 gives experiment of variable conditions and tools to verify constructed feed rate optimization and the result of experiment. Finally, Section 4 concludes the paper.

2. Optimized Algorithm

2.1 Cutting Force Model of Flat End Mill

The proposed cutting force model was constructed based on the following assumptions of conventional orthogonal cutting force model. The cutting force modeling was conducted on F_t because F_r is not involved in spindle load.

$$F_t(\phi) = K_{tc}ah(\phi) + K_{te}a \tag{1}$$

The Eq. (1) suggested the instantaneous tangential force when the angle of milling cutter is ϕ in Fig. 1. The average concept was applied to construct the compact instantaneous cutting force model. The average of tangential force could be calculated by integrating instantaneous force over revolution and dividing by the pitch angle. The Eq. (42) expressed average of tangential cutting force [2].

$$\overline{F_t} = \frac{1}{\phi_p}\int_{\phi_{st}}^{\phi_{ex}} F_t(\phi)d\phi \tag{2}$$

Substituting Eq. (1) into Eq. (2) and summarizes them, it could be expressed as Eq. (3).

$$\overline{F_t} = k_1 af(\cos(\phi_{st}) - \cos(\phi_{ex})) + k_2 a(\phi_{ex} - \phi_{st}) \tag{3}$$

The Eq. (3) is the final equation of cutting force model. It is consisted of a of axial depth, f of feed per tooth, ϕ_{st} of cutting entry angle, ϕ_{ex} of exit angle, and k_1, k_2 of cutting coefficient. The cutting coefficient could be obtained from data measured in actual cutting process. The other parameters such as a, f, etc. could be abstracted by cutting condition algorithm.

Experiment was conducted by setting a tool path in the shape of zig zag with various conditions such as depth, width and feed rate in order to obtain the cutting coefficient of mounted tool. The tool has two flutes, a diameter of 6 mm and HSS high-speed end mill and the workpiece was alumina-6061 in the shape of a rectangular. The results of experiment are summarized in Table 1.

Table 1 Measured cutting load of various conditions

Width / Depth	6 mm	2 mm	3 mm
1 mm	0.1302 Nm	0.0321 Nm	0.0595 Nm
1.5 mm	0.1972 Nm	0.0455 Nm	0.0825 Nm
2 mm	0.2385 Nm	0.0598 Nm	0.1008 Nm

The cutting coefficient of the experiment set was abstracted to k_1 of 0.2829 and k_2 of 0.0201.

2.2 Cutting Force Model of Ball End Mill

Many cutting force model of ball end mill were proposed. These model was developed based on empirical chip-force relationship. The dominant parameter that determined the cutting force is chip thickness. The chip thickness was determined by tool diameter, axial depth and several angular parameters such as tool rotation angle, lag angle, etc. [3], [4]. However, it is hard to abstract momentary parameters of these methods in various cutting conditions. Besides these cutting force models are difficult to apply to real time optimization because of amounts of computation.

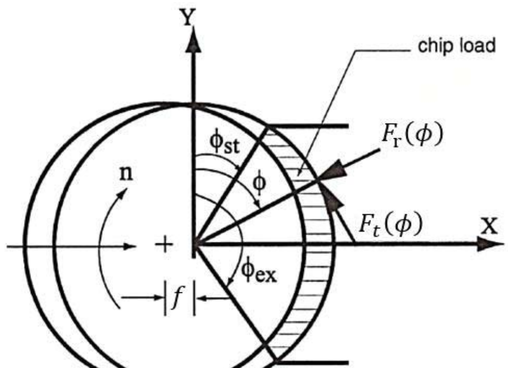

Fig. 1 Mechanism of milling process

In this paper, new method of cutting force model of ball end mill were suggested based on cutting force model of flat end mill. The difference of cutting process mechanism between flat end mill and ball end mill was analyzed from the perspective of slot and side milling. In the side milling process mechanism of flat end mill, the entire area of participating in the process will all proceed with side milling. On the other hand, slot milling and side milling are mixed according to the height of the tool in the ball end mill. In this way, the cutting force model of ball end mill could be constructed of two-phase regions in slot milling area and side milling area. In the slot milling area, the parameters of cutting entry and exit angle might be generally replaced with 0 rad and π rad respectively. The final tangential cutting force could be calculated by adding values of two-phase regions as Eq. (4).

$$\bar{F_t} = (2k_1 f + \pi k_2)z_1 + \left(k_1 f(\cos(\phi_{st}) - \cos(\phi_{ex})) + k_2(\phi_{ex} - \phi_{st})\right)z_2 \quad (4)$$

The depth of cut parameter of z_1, z_2 could be calculated by tool diameter and width of cut as Eq. (5).

$$z_1 = \frac{D-\sqrt{D^2-w^2}}{2}, \; z_2 = a - z_1 \quad (5)$$

The other parameters could be obtained by using the same cutting condition algorithm of the flat end mill.

Other experiment was performed to abstract cutting coefficients of the cutting force model of ball end mill. The tool of ball end mill used in the experiment was the same size and material as the flat end mill, and the workpiece was identical. The cutting conditions configured in the experiment were variable feed rate of 100 mm/min intervals from 200 to 500 and width of cut of slot milling of 6 mm and side milling of 4 mm. The depth of cut was constant at 2 mm. The result of ball end mill experiment are summarized in Table 2.

Table 2 Measured cutting load of ball end mill experiment

Width \ Feed	200	300	400	500
6 mm	0.091	0.136	0.183	0.203
4 mm	0.082	0.107	0.129	0.160

The cutting coefficient of cutting force model of ball end mill was abstracted to k_1 of 0.4514 and k_2 of 0.004072.

2.3 Abstracting Algorithm of Cutting Condition

The cutting condition used in cutting force model could be calculated from G-code applying to 3-axis CNC machining center. The parameter of a could be obtained by Z of position command, and the parameter of f could be calculated from S of spindle speed command and F of feed rate command. However, abstracting of cutting entry, exit angle is not that simple because it depends on remaining workpiece and time. The interpreter that calculates tool center point (TCP) over sample time from G-code was constructed to abstract cutting entry, exit angle by using MATLAB software. Based on the interpreter and tool diameter, a simulation was constructed to distinguish between the remaining and removed parts of the workpiece. At one sample time, the cutting entry, exit angle is calculated through the area of the tool and the remaining material overlapping at the location of the TCP.

Obtaining cutting coefficient parameter of cutting force model should be required measured cutting force data. Processing with various conditions of feed rate and width was carried out for abstracting cutting coefficient. Data learning methods of genetic algorithm and curve fitting were used to abstract cutting coefficient and the results were compared to increase the reliability of the cutting force model. The performance of the two methods was similar, but curve fitting was used as an optimization algorithm because of time of find the optimal value. However, due to the characteristics of the cutting coefficient, it is different for each tool or material. In addition, cutting coefficient may be formed differently depending on the environment such as tool mounting, temperature, lubrication, etc. in the same tool and material. In the future work, the feed rate optimization will be applied to CNC machine controller part of numerical control kernel. A built-in real time spindle load measurement system from machining center can solve this problem by updating the cutting coefficient.

2.4 Feed Rate Optimization

The optimized feed rate of flat end mill could be calculated from cutting force model Eq. (3) by passing the rest with only parameter f left on the right side.

$$f = \frac{\bar{F_t} - k_2 a(\phi_{ex} - \phi_{st})}{k_1 a(\cos(\phi_{st}) - \cos(\phi_{ex}))} \quad (6)$$

In the same way, the optimized feed rate of ball end mill could be calculated as Eq. (7).

$$f = \frac{\bar{F_t} - k_2[\pi z_1 + (\phi_{ex} - \phi_{st})z_2]}{k_1[2z_1 + (\cos(\phi_{st}) - \cos(\phi_{ex}))z_2]} \quad (7)$$

At the Eq. (6) and Eq. (7), the average tangential cutting force was decided on the highest force of one tool path created with recommended conditions. The remaining parameters would be calculated by applying the corresponding G-code line to the abstracting algorithm of cutting condition. The optimized feed rate of corresponding line would be obtained by Eq. (6) and Eq. (7). The new G-code was created by only adding feed rate commend F to existed G-code. The performance of feed rate optimization was verified by comparing the cycle time and cutting load of the actual experiments of existed G-code and new G-code.

3. Verification of Feed Rate Optimization

When the highest cutting load was criteria, the optimized feed rate was derived to large value under conditions of low depth. The cutting load at this feed rate is the same as the criteria, but it has a great adverse effect on the surface roughness and precision. Therefore, optimization was performed in the same cutting depth. The optimization of flat end mill experiment was performed, and the optimized feed rate are summarized in Table 43.

Table 34 Optimized feed rate of various conditions

Depth \ Width	6 mm	2 mm	3 mm
1 mm	500 mm/min	3576 mm/min	1603 mm/min
1.5 mm	500 mm/min	3576 mm/min	1603 mm/min
2 mm	500 mm/min	3576 mm/min	1603 mm/min

The optimized feed rate did not change depending on the cutting depth. The criteria cutting force was selected to 6 mm of cutting width and 500 mm/min of feed rate. The optimized feed rate was abstracted to 3576 mm/min of feed rate of 2 mm side milling and 1603 mm/min of feed rate of 3 mm side milling. The experiment was conducted by applying the optimized feed rate from each cutting conditions, and the results are shown in Table ~~5~~4.

Table ~~5~~4 Measured cutting load of optimized feed rate under each conditions

Depth (mm) \ Width (mm)		6	2	3
Feed rate (mm/min)		500	3576	1603
1	Cutting load (Nm)	0.1335	0.1311	0.1409
1.5	Cutting load (Nm)	0.2003	0.1898	0.1966
2	Cutting load (Nm)	0.2531	0.2371	0.2418

The cutting load of the optimized feed rate was maintained at a minimum of 93.7 %, a maximum of 105.5 % and an average of 98 % compared to the criteria cutting load. The cycle time was reduced by 30 % to 153 s after feed rate optimization from 216 s.

The feed rate optimization of ball end mill was performed under cutting conditions of various width of cut without changing the axial depth. The ratio of z_1 of slot milling area and z_2 of side milling area changes according to the width of cut. The criteria cutting force was selected based on the recommended cutting condition of tool hand book of 300 mm/min of feed rate. The width of cut was set at 1 mm intervals from 4 mm to 1 mm. The abstracted optimized feed rate under various conditions are summarized in Table 5.

Table 5 Optimized feed rate of ball end mill under various conditions

Width	6 mm	4 mm	3 mm	2 mm	1 mm
z_1 (mm)	2	0.764	0.402	0.172	0.042
z_2 (mm)	0	1.236	1.598	1.828	1.958
Feed rate (mm/min)	300	406	555	882	1932

The experiment was conducted by applying the derived optimized feed rate to the G-code. Table ~~7~~6 shows the result of feed rate optimization of ball end mill.

Table ~~7~~6 Result of feed rate optimization experiment of ball end mill

Width	6 mm	4 mm	3 mm	2 mm	1 mm
Feed rate (mm/min)	300	406	555	882	1932
Cutting load (Nm)	0.1573	0.1562	0.1563	0.1516	0.1502

The cutting load was maintained at a value similar to the criteria load of 6 mm slot milling. The cutting load of optimized feed rate condition is 97.7 % of average and 95.5 % of minimum compared to the criteria cutting load. The cycle time was reduced by 41 % to 66 s after feed rate optimization from 112 s. Based on the experimental result, the performance of the optimization and the accuracy of the cutting force model of ball end mill were simultaneously verified.

4. Conclusions

A model-based feed rate optimization for reduction of cycle time is presented. The optimization was performed with two types of tools: a flat end mill and a ball end mill. The cutting force model of flat end mill was derived based on the orthogonal and milling cutting model theories. The cutting force model of ball end mill was derived by dividing areas of slot milling and side milling from the cutting force model of flat end mill. The feed rate optimization algorithm was constructed based on the cutting force model and tool center point. The feed rate derived by optimization algorithm was applied to G-code feed rate command F. The performance of feed rate optimization was verified by applying the optimized feed rate to commercial machine tool. The feed rate optimization of flat end mill maintained the cutting load at an average of 98 % of the criteria cutting load, and the cycle time was reduced by 30 %. At the ball end mill case, the optimization maintained the cutting load at an average of 97.7 % of the criteria cutting load, and the cycle time was reduced by 41 %.

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