Optimization of Turning Process by Cutting Force Measurement*

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The needs of today's complex manufacturing systems requires the use of machine tools operated by means of an adaptively controlled system. Adaptive control provides continuous monitoring of performance and adjusts the system variables in order to approach the conditions optimum for the chosen performance objectives. This investigation proposes the in-process parameter estimation method of tool life in turning, in which the force ratio of feed force to tangential force due to the tool wear is detected. The method involves the analysis of the optimum cutting conditions based on the machining cost per unit volume of metal removed under the considered cutting constraints.

Key Words: Cutting, Cutting Force, Adaptive Control, Recursive Least Squares Method

1. Introduction

The increasing capital cost for machine tools, especially numerically controlled, makes efficient their utilization increasingly important. The selection of the optimum cutting conditions is an essential factor in economical utilization. An effective method aimed at solving this problem is called adaptive control (AC).

In machine tool control systems, AC is mainly divided into two classes: adaptive control constraint (ACC) and adaptive control optimization (ACO). ACC systems involve cutting conditions that are always subject to limits provided by the machine tool, tool and/or workpieces. ACO systems are another type of control system. In such systems, cutting conditions are determined by using a performance index based on production economy.

In the ACO system developed by Centner and

Idelsohn⁽¹⁾, it was necessary to detect the tool wear rate. Takeyama et al.⁽²⁾ developed a system which selected the optimum cutting conditions through in-process measurement of cutting forces. In this investigation, the application of the force ratio of feed force to tangential force and the recursive least squares method for on-line estimation of tool life is proposed to determine the optimum cutting conditions.

2. Performance Index

The principal objective of any optimization analysis of machining problems is to select the values of the machining parameters so that a chosen combination of them will be optimum, leading to either minimum cost, maximum production rate, or maximum profit rate. The machining cost per unit volume of metal removed can be determined by

$$K = \frac{K_1 T + K_1 \tau + K_2}{1000 a f V T}, \quad (1)$$

where K is the machining cost per volume of metal removed (¥/mm³); K_1 is the machining cost rate (¥/min); K_2 is the tool cost (¥/cutting edge); τ is the tool changing time (min); V is the cutting speed (m/min); f is the feed (mm/rev); a is the cutting depth

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(mm); and T is the tool life (min). The analysis of optimum cutting conditions makes use of the tool life equation for the given combination of the cutting tool, work material and cutting condition in the form of Taylor's equation as

$$TV^n f^m = C, \quad (2)$$

where n , m and C are constants. Namely, if the parameters (n , m and C) included in Eq. (2) are known exactly, it is possible to select the optimum cutting conditions. These parameters, however, take different values for various combinations of tool and workpiece materials. Therefore, many measurements are necessary to determine these values.

Although abundant tool life data have been reported in various publications, such information is not always applicable to a particular job or specially to new work materials or tool materials. Therefore, the tool life equation must be determined or estimated by some means for such specific cases. The usual practice in obtaining a tool life relationship is to conduct an elaborate tool life test at a machinability laboratory under pre-designed test conditions and tool life criteria which is usually based upon either a predetermined flank wear limit or crater wear. These tool life tests are time consuming and expensive. Also, there is no guarantee that these tool life data under laboratory test conditions can be readily applicable to actual production operations with a machine tool in a workshop.

To improve the possible discrepancy of such laboratory-tested tool life data and also for such a case as when previously tested tool life data are not available, Hitomi⁽³⁾ proposed a method called "optimum seeking machining" to estimate the tool life parameters using production data available from actual workshop operations.

Yonetsu et al.⁽⁴⁾ applied a recursive estimation method to estimate parameters included in Taylor's equation and extended the control method to adaptive control by applying various perturbation methods.

Since, in on-line control, the direct measurement of tool wear or tool wear rate is extremely difficult, it is necessary to detect, in an on-line fashion, another measurable signal representing the tool wear. As described in previous research^{(5),(6)}, the cutting force is most practical and reliable for this purpose.

3. Tool Wear and Force Ratio

Many attempts have been made at wear estimation by means of the cutting force components^{(2),(5),(6)}. The cutting force components in turning are defined in Fig. 1. In order to measure tool wear, the effects of the variables on the cutting forces are summarized in the empirical equation for the i^{th} component as

$$F_i = K_i V^{a_i} f^{b_i} a^{c_i}, \quad (3)$$

where F_i is the cutting force (N); K_i is the specific cutting force; and a_i , b_i and c_i are the exponents in the force equation. "i" indicates the cutting directions. This is a complex task requiring a large amount of data to cover all combinations of tool and work materials.

In order to obtain a reasonable measurement of tool wear during cutting, one method is the use of the ratio of cutting force components. The use of the force ratio as an indicator of tool wear must be validated by demonstrating that the effects of the variables are sufficiently small and that tool wear has a measurable effect on the force ratio. Twelve types of force ratios are used to indicate the tool wear.

$$\begin{aligned} R_1 &= \frac{F_p}{F_t} & R_2 &= \frac{F_f}{F_t} & R_3 &= \frac{F_f}{F_p} \\ R_4 &= \frac{F_p}{\sqrt{F_p^2 + F_f^2 + F_t^2}} & R_5 &= \frac{F_t}{\sqrt{F_p^2 + F_f^2 + F_t^2}} \\ R_6 &= \frac{F_f}{\sqrt{F_p^2 + F_f^2 + F_t^2}} & R_7 &= \frac{F_p}{\sqrt{F_p^2 + F_t^2}} \\ R_8 &= \frac{F_t}{\sqrt{F_p^2 + F_t^2}} & R_9 &= \frac{F_p}{\sqrt{F_p^2 + F_f^2}} \\ R_{10} &= \frac{F_f}{\sqrt{F_p^2 + F_f^2}} & R_{11} &= \frac{F_t}{\sqrt{F_f^2 + F_t^2}} \\ R_{12} &= \frac{F_f}{\sqrt{F_f^2 + F_t^2}} \end{aligned} \quad (4)$$

Figure 2 shows the increase in the force ratios for a 0.2 mm-worn tool. The force ratio of the feed force to the tangential force has the maximum increasing ratio. Therefore, this force ratio should be used to indicate the tool wear. In this investigation, the force ratio (R) of the feed force (F_f) to the tangential force (F_t) is used as an indicator of tool wear.

Another advantage derived from the use of force ratio,

$$R = \frac{F_f}{F_t}, \quad (5)$$

Fig. 1 Cutting force components in turning

can be explained by taking the ratio of the i^{th} the cutting force component as

$$\frac{F_f}{F_t} = \frac{K_f}{K_t} V^{(a_f - a_t)} f^{(b_f - b_t)} a^{(c_f - c_t)} \quad (6)$$

Since c_f and c_t in Eq. (6) are approximated to 1 for different tool-work material combinations, the effect of cutting depth is ignored. Thus

$$\frac{F_f}{F_t} = \frac{K_f}{K_t} V^{(a_f - a_t)} f^{(b_f - b_t)} \quad (7)$$

or

$$R = K_R V^{a_R} f^{b_R} \quad (8)$$

where K_R is the specific force ratio, and a_R and b_R are the exponents in the force ratio equation. The relationships between the force ratio (F_f/F_t) and the cutting conditions in Fig. 3 can be summarized that the increasing cutting speed and feed effect a decreasing force ratio, while the change of cutting depth does not directly affect the force ratio. Therefore, in on-line measurement, the variation of force ratio depends directly on the wear state but not on the cutting depth. However, to assess the actual amount of wear (maximum allowable wear), the relationship between the force ratio and the wear must be determined.

In order to investigate the influence of cutting conditions on the force ratio, a new tool and a 0.33 mm-worn coated tool are tested. Figure 4 shows the results from the series of tests at constant cutting depth of 1.5 mm. The results indicate that the force ratio of the new tool decreases when cutting speed and/or feed increases. For the 0.33 mm-worn tool, the increase of feed decreases the force ratio, similarly as the new tool, but it is opposite to the increase of cutting speed. To compensate for the effect of cutting speed and feed, the relationship of Eq. (8) must be solved. During cutting, the cutting speed and feed at any instant are known, and by using the predeter-

Fig. 2 Increase in the force ratio of 0.2 mm-worn tool to new tool

mined characteristic, a compensated value of the force ratio can be computed.

Since flank wear is usually the major criterion of wear, a set of cuts in which this type of wear occurs is made to determine the force ratio versus flank wear. Results from one such test are shown in Fig. 5. It demonstrates that the change of the force ratio is proportional to the amount of flank wear and time. This relationship is represented by a linear model to a good degree of approximation. When cutting conditions change, the slope of the line changes as shown in Fig. 6. The model is designed to take the form

$$R_i(V_i, f_i, t) = R_{0i}(V_i, f_i) + S_i(V_i, f_i) \times t, \quad (9)$$

where $R_i(V_i, f_i, t)$ is the force ratio of cutting condition i at time t . $R_{0i}(V_i, f_i)$ and $S_i(V_i, f_i)$ are the initial force ratio and slope of force ratio at cutting condition i . When substituting t with the tool life (T_i), R_i changes to the force ratio at tool wear (R_{wi}) at which

Fig. 3 Influences of cutting conditions on force ratio

Fig. 4 Relationships of force ratios and cutting conditions
Tool: U610, Work: SNCM439

Fig. 5 Relationships of cutting force, wear and time

Fig. 6 Relationships of force ratio, tool wear and time

the tool should be replaced. Thus,

$$R_{wi}(V_i, f_i) = R_{oi}(V_i, f_i) + S_i(V_i, f_i) * T_i \quad (10)$$

or

$$T_i = \frac{R_{wi}(V_i, f_i) - R_{oi}(V_i, f_i)}{S_i(V_i, f_i)} \quad (11)$$

In order to estimate the tool life, the difference between force ratio [$R_{wi}(V_i, f_i) - R_{oi}(V_i, f_i)$] and the slope of force ratio in Eq. (11) must be investigated. The differences of force ratio were measured and are shown in Figs. 4(C) and (D). The results show that the difference between force ratio of both tools increases when cutting speeds increase. The increase of differences in force ratio is linear when cutting speeds are between 100–300 m/min [Fig. 4(C)]. For increasing feed rate, the differences in force ratios of

both tools decreases, as shown in Fig. 4(D). This is opposite to the effect of cutting speeds. However, for the increase in cutting speeds and feeds, the differences in force ratio of both tools are influenced by the increase of cutting speed more than by feed rate.

For on-line estimation of the slope of the force ratio, the recursive least squares method is proposed in the following section. Finally, the T_i , V_i and f_i correlated with the machining cost and Taylor's equation using Eqs. (1) and (2) can be derived to determine the optimum cutting conditions.

4. Estimation of Process Parameters

The real-time estimation of the slope of force ratio (S_i) in Eq. (9) can be accomplished by the recursive estimation method⁷⁾. In this investigation, the recursive least squares (RLS) algorithm is utilized as follows:

$$\theta(t) = \theta(t-1) + \frac{P(t-1)\phi(t)[y(t) - \phi(t)^T\theta(t-1)]}{\lambda(t) + \phi(t)^TP(t-1)\phi(t)} \quad (12)$$

$$P(t) = \frac{1}{\lambda(t)} \left[P(t-1) - \frac{P(t-1)\phi(t)\phi(t)^TP(t-1)}{\lambda(t) + \phi(t)^TP(t-1)\phi(t)} \right], \quad (13)$$

where $y(t)$ is the measured output at time $t = k\Delta t$ for $k=1, 2, 3, \dots$; $\phi(t)$ is the vector of measured variables; $\lambda(t)$ provides exponential data weighting; and $\theta(t)$ is the vector of estimated parameters. The $P(t)$ is the gain matrix. The algorithm recursively updates the estimated parameter vector $\theta(t)$ for any process whose equations can be written in the form,

$$y(t) = \phi(t)^T\theta(t). \quad (14)$$

Thus, the process model must be written in a form that gives a linear relationship for the unknown parameters, which are the elements of the vector $\theta(t)$. For the process model presented in the previous section, the estimation of S_i and R_{0i} using Eq. (9) is considered as follows:

$$R_i(t) = [1 \ t] \begin{bmatrix} R_{0i}(t) \\ S_i(t) \end{bmatrix}. \quad (15)$$

Hence, the estimation algorithm in Eqs. (12) and (13) is used with

$$y(t) = R_i(t) \quad (16)$$

$$\phi(t)^T = [1 \ t] \quad (17)$$

and

$$\theta(t)^T = [R_{0i}(t) \ S_i(t)] \quad (18)$$

to estimate $S_i(t)$. The RLS estimation algorithm requires the initial values for $\theta(0)$ and $P(0)$. If some prior information on $\theta(0)$ is available, it should of course be used for determining the suitable values of $\theta(0)$ and $P(0)$. If no prior information is available, the most common choice is to take

$$\theta(0) = 0 \quad (19)$$

and

$$P(0) = \delta I, \quad (20)$$

where " I " is the identity matrix and δ is some large constant. The RLS algorithm is typically insensitive to the choice of $\theta(0)$ and $P(0)$.

The choice of the weighting factor $\lambda(t)$ in Eqs. (12) and (13) is significant. The standard RLS algorithm is obtained when $\lambda(t)=1$. When it is necessary to track parameters with values that may jump or vary slowly with time, a value of $0 < \lambda(t) < 1$ exponentially weights the data to ensure the alertness of the algorithm. In some sense, as $\lambda(t)$ is decreased, the algorithm remains more alert to changes in the estimated parameters. Typically, it has often been useful to let $\lambda(t)$ grow exponentially with t to 1. This can be written as

$$\lambda(t) = \lambda_o \lambda(t-1) + (1 - \lambda_o), \quad (21)$$

where λ_o is the adjusting rate. If the parameters change slowly and the primary concern is the final values, then the choice of $\lambda(t)$ is not so important since the estimator will finally converge to the correct values. However, when the performance during parameter convergence is significant, the choice of $\lambda(t)$ is more important. When $\lambda(t)$ is closed to 1.0, the estimator reacts more slowly than when $\lambda(t)$ is small. However, as $\lambda(t)$ becomes small, the abundance of the input becomes more of an issue. In this investigation, the values of $\lambda_o=0.99$ and $\lambda(0)=0.95$ of the weighting factor determined by Eq. (21) are utilized.

Fig. 7 The experimental setup

5. Experimental Results

The experimental setup is illustrated in Fig. 7. All experiments were conducted in a NC-turning machine (Okuma LB-10 CV-12) with a 5.5 kW spindle motor. A Kistler dynamometer was utilized in order to measure the cutting force. The dynamometer was mounted on the tool carriage. The three components of cutting force signals were preamplified and fed together through a 12-bit 8-channel A/D-converter into a Hewlett-Packard stand-alone microcomputer. The digitizing of signals was done simultaneously by a fast-assembler on-line monitoring loop. Experimental results presented in this investigation were obtained from SNCM439 (HB250; work material) and U610 (TNMG332; coated tool).

A series of experiments was performed to determine the relationship between cutting conditions and force ratio for a 0.33 mm-worn tool. For a new tool, two series of experiments were performed. One was the determination of the relationship between cutting conditions and initial force ratio of the preworn tool. The other was a series of tests to estimate the slope of force ratio of each cutting condition by means of the RLS method. The preworn tool was used confirm that the experimental results for estimating the slope of force ratio were in the second state of tool wear.

The RLS algorithm in Eqs. (12) and (13) is used to estimate the slope of force ratio using Eq. (15). The estimation of the slope of force ratio is shown in Fig. 8. Since the slope of force ratio was zero at the initial state, the change of the slope of force ratio was rapid in the first 6 s of the estimation. The results show that the proposed method can rapidly estimate the slope of force ratio. The cutting test under particular cutting conditions is carried out for about 40 s, in which the estimation of the slope of force ratio is obtained. Especially when higher cutting speeds are tested, the slope of force ratio can be estimated quickly. The results demonstrate that the slope of force ratio is much more predominantly affected by cutting speed than by feed.

The obtained results are utilized to calculate tool life using Eq. (11). Then, the cutting conditions and tool life calculated in Eq. (11) are correlated to estimate the tool life parameters (n , m and C) in Taylor's equation. After the machining cost can be computed, the cutting conditions are altered under the machining constraints to achieve the optimum cutting conditions. The contour map of machining cost can then be plotted against the cutting conditions, as shown in Fig. 9. The optimum cutting conditions are found on the interception of maximum feed and constant power. The reason why the optimum cutting condition is

Fig. 8 Estimations of slope of force ratio by means of RLS

Fig. 9 Contour map of machining cost and cutting conditions

Tool : U610, Work : SNCM439, $K \times 10^{-4} (\text{¥/mm}^3)$

Fig. 10 Simulation of optimum cutting condition using the optimum gradient method

Tool : U610, Work : SNCM439, $K \times 10^{-4} (\text{¥/mm}^3)$

found on the side of higher feed is that the metal removal rate is proportional to cutting speed and feed, but tool life is much more predominantly governed by cutting speed than by feed when minimizing the machining cost-per-unit volume of metal removed.

In order to investigate the optimum cutting conditions, the optimum gradient method⁽⁸⁾ is utilized. A simulation of a 1 mm cutting depth is shown in Fig. 10. The simulation of two different initial cutting conditions (V, f) is performed. The results show that the optimum gradient method can conduct a search to determine the solution efficiently. In particular, when the initial cutting condition (start 2) selected is high, the simulation uses a shorter time for computation.

6. Conclusions

For the optimization of cutting conditions in the turning process, the measurement of the force ratio of feed force to tangential force and the application of the recursive least squares method for the estimation of tool life were proposed. The results are summarized:

1. The force ratio of feed force to tangential force can be utilized to detect the tool wear.
2. The application of the recursive least squares method to estimate the tool life can reduce the testing cost in the determination of the optimum cutting conditions.
3. The proposed method is feasible for use in the adaptive control system.

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