Journal of the Operations Research
Society of Japan
Vol. 45, No. 1, March 2002



# DYNAMIC MACHINING PROJECT CONTROL MODEL UNDER ORDER QUANTITY AND DEADLINE CONSTRAINTS

Tian-Syung Lan
*Tatung University*
*De Lin Institute of Technology*

Chun-Hsiung Lan
*Tungnan Institute of Technology*

Long-Jyi Yeh
*Tatung University*

(Received February 19, 2001; Final September 13, 2001)

*Abstract* To achieve the optimal control of material removal rate (*MRR*) for a machining project, a Dynamic Machining Project Control (*DMPC*) Model is proposed under the considerations of order quantity and deadline constraints. This paper not only introduces material removal rate into the objective function dynamically, but also implements Calculus of Variations to resolve the continuous control problem comprehensively. In addition, the optimal solution to minimize the cost of a machining project with production deadline is provided, and the decision criteria for selecting the optimal solution are recommended. Moreover, the sensitivity analyses of decision variables in the optimal solution as well as the numerical simulation of a real industrial problem are fully discussed. This study contributes a significant approach to control a machining project for production engineers in today's machining industry with profound insight.

## 1. Introduction

The cutting speed, feed rate and depth of cut were considered as three factors of input cutting parameters [14]. To calculate the optimum cutting conditions is the objective for production [13]. Rash and Rolstadas [16] used a mathematical model to determine optimum feed and speed for turning operations; however, the equations developed are limited to typical machines only. Koren *et al.* [11] have also described several methods to be used under stepwise constant variation in feed, speed, or depth of cut, but none is practically applicable when two or more cutting conditions are changed. Therefore, controlling cutting conditions with fixed material removal rate has been introduced [1, 3].

The *MRR* is used widely in adaptive controllers for optimization of machining operations [10]. With the design of a variable structure system (*VSS*) controller on commercial computer numerical controlled (*CNC*) turning machines [5], the material removal rate is dynamically manageable through overriding the spindle speed. These PC-based controllers have also been implemented to on-line override the programmed feedrate on the *CNC* milling machines [17] as well as on the machining centers [9]. Therefore, by overriding the feedrate and/or spindle speed on various *CNC* machines, the material removal rate is surely capable of being dynamically controlled for most machining operations.

In addition, the tool life is also a critical parameter of the machining process [3]. Novak and Wiklund [15] proposed a suitable implementation to predict tool life, and Lee *et al.* [12] proposed a method of optimal control to ensure maximum tool life. Meng *et al.* [13] also provided a modified Taylor tool life equation to minimize tool cost. As a matter of fact, the maximum tool life or the minimum tool cost will not guarantee the minimal cost of a machining project. Besides, the various tool checking periods for tool change from different machine tool operators will decrease the productivity and increase the cost of a machining project significantly. In order to manage the consumption of tools well, a fixed tool life is then practically considered into the machining project in this study.

Although several time series modeling on the control of machining process are mentioned [8], none is guaranteed to achieve minimum cost. They are mostly emphasizing on the maximal tool usage. Actually, the machining cost and the production deadline are mainly concerned problems for a machining project confronting the manufacturing industry. The cost to machine each part is a function of the machining time [6]. While the marginal cost of production is a linear increasing function of production rate [7], the marginal cost of machining operation is also considered to be a linear function of *MRR* in this study. This denotes that the higher machining rate results higher operational cost, such as machine maintenance and machine depreciation costs. Besides, Soroush [18] mentioned that meeting the production deadline is the most desirable objective of management. It is that an earlier completed order will freeze the capital, raise the inventory cost, and indicate the sub-optimal resource utilization. On the other hand, an order completed later than the production deadline may lose customers. Therefore, meeting the deadline of an order is critical to production projects.

The interest in the minimum-cost production control grows up in modern manufacturing systems with the necessity of being more and more flexible to match the order quantity and production deadline. As the modern computer numerical controlled (*CNC*) machines are widely used to perform from job shops to flexible manufacturing systems (*FMS*) [19], there is an economic need to dynamically control the material removal rate with fixed tool life during the machining operation of a production project. The material removal rate is an important control factor of a machining project, and the control of machining rate is also critical for production planners. Hence, it is essential to find the optimum solution of *MRR* control for a machining project to not only reach the minimal cost but also meet the order quantity at the production deadline. The *DMPC* Model proposed in this study provides the practical solution to the technique, and contributes the significant approach to control a machining project for the industry.

## 2. Assumptions and Notations

Before formulating the problem, several assumptions and notations are to be made. They are described as follows:

### 2.1. Assumptions

1. The production project is a single-tool and continuous machining operation on one *CNC* machine.
2. The order quantity $Q$ is considered as the production assignment to the controlled machine.
3. The upper limit of *MRR* is generated from the maximum allowable cutting conditions suggested in the handbook, and the fixed tool life is derived from the Taylor's expression of the tool life [4] with these maximum conditions. Thus, no tool will break before this fixed tool life even with the upper *MRR* limit.
4. There is no chattering or scrapping of parts occurs during the whole manufacturing process.
5. The time required for a tool change is relatively short to the tool life, and it is neglected.
6. All chip from cutting and the finished parts are held and stored at the machine until the whole machining project is done, and the entire order should be accomplished for the customers exactly at the production deadline.

7. The marginal cost of operation is considered to be a linear function of the material removal rate [7].
8. The machining speed of a tool is continued and controlled following the final machining speed of the previous tool.

### 2.2. Notations

$a$ : average volume of material machined per unit part.
$B$ : upper limit of material removal rate.
$\overline{B}$ : fixed $MRR$ for traditional machining model.
$bx'(t)$ : marginal operation cost [7] at the material removal rate $x'(t)$; where $b$ is a constant.
$bx'^2(t)$ : operational cost [7] at time $t$.
$c$ : overall holding cost per unit chip machined per unit time at the machine; including chip holding cost per unit chip machined per unit time, and part holding cost per unit chip machined per unit time.
$c_l$ : labor cost of a machine per unit time; including production and queuing.
$c_s$ : tool cost of a tool per unit machining time for *DMPC* Model, where $c_s = \dfrac{c_t}{t_l}$.
$\overline{c}_s$ : tool cost of a tool per unit machining time for traditional machining model, where $\overline{c}_s = \dfrac{c_t}{\overline{t}_l}$.
$c_t$ : tool cost per tool, including cost of tool and tool set-up cost.
$O_b$ : production cost for *DMPC* Model.
$\overline{O}_b$ : production cost for traditional machining model.
$Q$ : order quantity of the machining project.
$T$ : production deadline that is given by the customer.
$t_l$ : fixed tool life for *DMPC* Model.
$\overline{t}_l$ : fixed tool life for traditional machining model.

### 2.3. Decision functions

$x(t)$ : cumulative volume of material machined during time interval $[t_x, t]$, where $t_x$ is the queuing time before production.
$x'(t)$ : material removal rate at time $t$.

## 3. Model Formulation

In this study, $x(t)$ is time continuous and differentiated [2, 7]. Therefore, $\int_{t_x}^{T} \left[bx'^2(t) + cx(t) + c_s\right] dt$ denotes the operation cost, overall holding cost and tool cost during the time interval $[t_x, T]$. Besides, $c_lT$ represents the labor cost during the production deadline period $[0, T]$. In addition, it is noted that the upper limit of material removal rate $B$ must satisfy $B \geq \dfrac{aQ}{T}$; otherwise, the machining operation will never meet the order quantity at production deadline. Thus, the objective function and its constraints for the machining project with order quantity and deadline constraints are constructed as below.

$$
DMPC \begin{cases} \min\limits_{x} \left\{ \int_{t_x}^{T} [bx'^2(t) + cx(t) + c_s]dt + c_lT \right\} \\ \text{s.t.} \quad x(T) = aQ \\ \qquad x(t_x) = 0, \quad 0 \leq t_x \leq T \\ \qquad 0 \leq x'(t) \leq B \quad \text{for } t \in [t_x, T] \end{cases}
$$

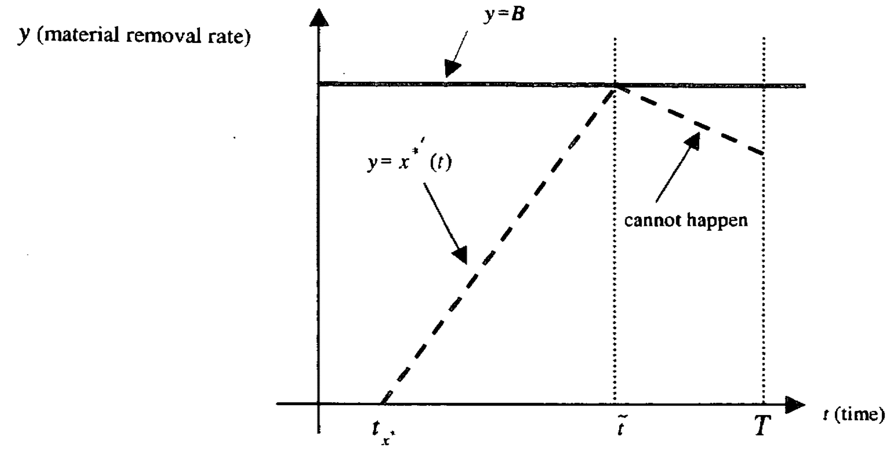


Figure 1: Possible condition of $y = x^{*'}(t)$

## 4. Optimal Solution

Set $x^*$ to be the optimal solution of *DMPC* Model, and set $t_{x^*}$ to be the optimal queuing time before production. Also, assume that the time interval $[t_{x^*}, \tilde{t}]$ is the maximal subinterval of $[0, T]$ to satisfy Euler Equation [2, 7].

There are two possible situations to be discussed in this study.

### 4.1. Situation 1: $x^{*'}(t)$ does not touch $B$ before $T$

The optimal solution for *Situation* 1 is shown as follows:

$$x^{*'}(t) = \frac{c}{2b}(t - t_{x^*}) + \sqrt{\frac{c_s}{b}}, \tag{1}$$

$$x^{*}(t) = \frac{c}{4b}(t - t_{x^*})^2 + \sqrt{\frac{c_s}{b}}(t - t_{x^*}), \tag{2}$$

$$t_{x^*} = T - 2\left(\frac{\sqrt{bc_s + abcQ} - \sqrt{bc_s}}{c}\right). \tag{3}$$

The detailed processes are described in Appendix A.
Here, a Property is proposed and discussed as follows:

**Property**: If the line $y = x^{*'}(t)$ touches the line $y = B$, two lines should overlap to be $y = B$ from the touch point $\tilde{t}$ to the end point $T$.

*Proof*: From Eq. (1), $x^{*'}(t)$ is a strictly increasing linear function of $t$. And it holds for any subinterval satisfying $0 \leq x^{*'}(t) \leq B$ during $[t_{x^*}, T]$. Therefore, $x^{*'}(t)$ in the time interval $[\tilde{t}, T]$ (shown in Figure 1) cannot exist because it contradicts the Euler Equation [2, 7] to be a decreasing linear function of $t$, the Property is then verified.

### 4.2. Situation 2: $x^{*'}(t)$ touches upper limit $B$ at time $\tilde{t}$ before $T$; where $\tilde{t} < T$

The optimal solution for Situation 2 is shown as follows:

$$\tilde{t} = T - \left(\frac{acQ - bB^2 + c_s}{Bc}\right), \tag{4}$$

$$t_{x^*} = T - \left(\frac{acQ + bB^2 - 2B\sqrt{bc_s} + c_s}{Bc}\right), \tag{5}$$

$$x^*(t) = \begin{cases} \dfrac{c}{4b}(t-t_{x^*})^2 + \sqrt{\dfrac{c_s}{b}}(t-t_{x^*}), & \text{for } t \in [t_{x^*}, \tilde{t}) \\ B(t-\tilde{t}) + \dfrac{bB^2 - c_s}{c}, & \text{for } t \in [\tilde{t}, T]. \end{cases} \tag{6}$$

The detailed processes for the solutions above are described in Appendix B.

The algorithm in achieving the optimal solution of the *DMPC* Model provides a continuous function indicating the optimal path to be followed by the variables through time or space. Using the properties of the Calculus of Variations for dynamic optimization, the completeness and the optimality of the solution are guaranteed [2, 7]. Additionally, the time and space complexity of the algorithm are not discussed in the study because the *DMPC* Model concludes the exact solution without search.

### 4.3. Decision criteria

From Eq. (2), the maximum value of $x^*(t)$ is found at $t = T$ and $t_{x^*} = 0$. That is, the range of $x^*(t)$ for Situation 1 is $\left[0, \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T\right]$. Therefore, the following criteria are made.

1. If $aQ \leq \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T$, $x^{*'}(t)$ will not reach the upper limit $B$ before $T$.
2. If $aQ > \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T$, $x^{*'}(t)$ will reach the upper limit $B$ before $T$.

Thus, when $aQ \leq \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T$, $x^{*'}(t)$ will not reach the upper limit $B$ before $T$; the optimum solution is Situation 1. When $aQ > \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T$, $x^{*'}(t)$ will reach the upper limit $B$ at $\tilde{t}$ before $T$; the optimum solution is Situation 2.

## 5. Sensitivity Analyses

The sensitivity analyses for the two feasible cases are discussed as follows:

### 5.1. The sensitivity analysis for Situation 1

From Eq. (3), it is claimed that $t_{x^*}$ is decreasing with $b, a$, or $Q$. It shows that increasing marginal operation cost, material volume per unit part machined, or order quantity may shorten the queuing time before production. Besides, $t_{x^*}$ is increasing with the production deadline $T$.

By Eq. (1), (2) and (3), the cumulative volume of material machined $x^*(t)$, and material removal rate $x^{*'}(t)$ is increasing with order quantity $Q$, material volume per unit part machined $a$, or marginal operation constant $b$; and decreasing with production deadline $T$. The overall sensitivity analysis for Situation 1 is shown in Table 1.

Table 1: The sensitivity analysis for Situation 1.

| Parameter / Decision Variables | $b$ | $a$ | $Q$ | $T$ | Reference |
|---|---|---|---|---|---|
| $t_{x^*}$ | − | − | − | + | Eq. (3) |
| $x^*(t)$ | + | + | + | − | Eq. (2) and (3) |
| $x^{*'}(t)$ | + | + | + | − | Eq. (1) and (3) |

"+": Decision variable is an increasing function of the parameter.
"−": Decision variable is a decreasing function of the parameter.

### 5.2. The sensitivity analysis for Situation 2

From Eq. (4), it is derived that the time to reach upper limit $\tilde{t}$ is increasing with marginal operation constant $b$ or production deadline $T$; and is decreasing with tool cost $c_s$, order quantity $Q$, or material volume per unit part machined $a$. In addition, it is asserted by Eq. (5) that the queuing time before production $t_{x^*}$ is increasing with production deadline $T$, and is decreasing with order quantity $Q$ or material volume per unit part machined $a$.

Moreover, from Eq. (4), (5) and (6), the cumulative volume of material machined $x^*(t)$ is increasing with the material volume per unit part machined $a$ or order quantity $Q$; and is decreasing with production deadline $T$. The overall sensitivity analysis for Situation 2 is shown in Table 2.

Table 2: The sensitivity analysis for Situation 2.

| Parameter / Decision Variables | $c_s$ | $b$ | $a$ | $Q$ | $T$ | Reference |
|---|---|---|---|---|---|---|
| $\tilde{t}$ | − | + | − | − | + | Eq. (4) |
| $t_{x^*}$ | # | # | − | − | + | Eq. (5) |
| $x^*(t)$ | # | # | + | + | − | Eq. (4), (5) and (6) |

"+": Decision variable is an increasing function of the parameter.
"−": Decision variable is a decreasing function of the parameter.
"#": Decision variable depends on the changes of other relevant parameters.

## 6. Numerical Simulation

To demonstrate the extensive versatility of the *DMPC* Model, a numerical case from real-world industry is studied. The machining project of a single-tool turning operation for specific fixture plates from AirTAC Corporation in Taiwan, R.O.C. is referenced for the simulation. The order quantity is assigned to a MIYANO LX-21 *CNC* lathe. All data compiled are transformed into SI units as well as US dollars. They are listed as follows:

$Q = 4000$ parts, $T = 7000$ min, $a = 17355$ mm$^3$, $b = 1.7 \times 10^{-8}$(dollars−min)/mm$^6$,
$c = 6.625 \times 10^{-8}$dollars/(min−mm$^3$), $B = 16470$mm$^3$/min,
$c_l = 0.135$dollars/min, $c_t = 6.523$dollars, $\bar{t}_l = 70$ min, and $t_l = 40$ min.

To compare the *DMPC* and traditional machining models on the aspect of production cost, a computer program written in VISUAL BASIC is then developed. The concept of the flow chart is described as follows:

$Q, T, a, b, c, B, c_l, c_t, \bar{t}_l$ and $t_l$ should be given before the following algorithm

*Step* 1: Compute $\overline{B} = \dfrac{aQ}{T}, \bar{c}_s = \dfrac{c_t}{\bar{t}_l}$, and $c_s = \dfrac{c_t}{t_l}$;

then compute the production cost, $\overline{O}_b = b\overline{B}^2 T + \dfrac{c\overline{B}T^2}{2} + \bar{c}_s T + c_l T$ for traditional machining model.

Go to *Step* 2.

*Step* 2: If $aQ > \dfrac{c}{4b}T^2 + \sqrt{\dfrac{c_s}{b}}T$, go to *Step* 4; otherwise go to *Step* 3.

*Step* 3: Compute $t_x$, then compute the production cost for *DMPC* Model.

$$O_b = \int_{t_x}^{T} \left[ bx'^2(t) + cx(t) + c_s \right] dt + c_l T.$$

Go to *Step* 5.

*Step* 4: Compute $\tilde{t}$ and $t_x$, then compute the production cost for *DMPC* Model.

$$O_b = \int_{t_x}^{\tilde{t}} \left[ bx'^2(t) + cx(t) + c_s \right] dt + \int_{\tilde{t}}^{T} \left[ bB^2 + c(x(\tilde{t}) + B(t - \tilde{t})) + c_s \right] dt + c_l T.$$

Go to *Step* 5.

*Step* 5: Write $t_{x^*}$ and $O_b$ for *DMPC* Model, and $\overline{O}_b$ for traditional model.

From the simulated result shown in Figure 2, it is observable that the production cost of *DMPC* Model is \$1467 dollars less costly than the traditional machining model, which is considered cost competitive through years of experiences in AirTAC Corporation. In addition, the optimal queuing time $t_{x^*} = 10.7288$ min can always be used for machine setup, machine maintenance, or material handling. The result of this numerical study shows good agreement with the *DMPC* Model in minimizing the production cost of a machining project.

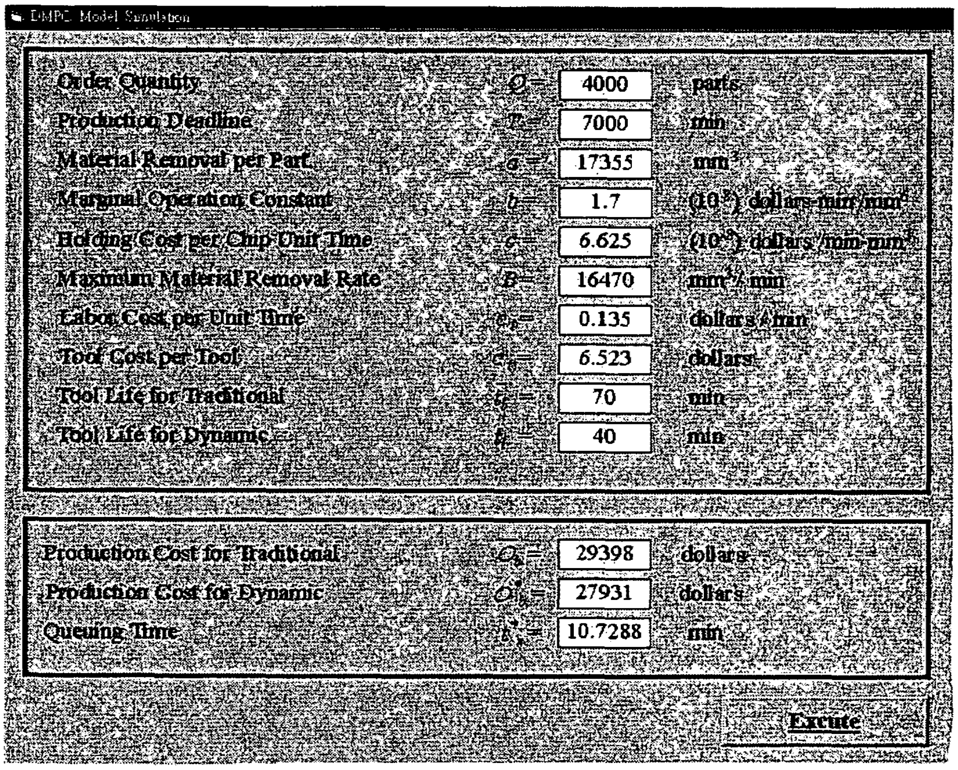


Figure 2: Cost simulation for *DMPC* and traditional models

## 7. Conclusions

The fixed tool life, tool cost, operation cost, holding cost, production deadline, order quantity, volume of material machined per unit part, and upper limit of *MRR* are considered simultaneously to determine the optimal control of material removal rate and the queuing time before machining. This is an extremely hard-solving and complicated issue. However, the problem becomes concrete and solvable through the *DMPC* Model.

In addition, the characteristics of this study are illustrated as follows: First, the optimal material removal rate $x^{*'}(t)$ is a strictly increasing linear function of $t$ before reaching the upper speed limit. Second, by Property described before, if the optimal *MRR* $x^{*'}(t)$ touches the upper limit $B$; it will stay to be the upper limit $B$. Third, from the optimal solution proposed in Section 4; the optimal number of tools required for the project can be determined by $\left[\frac{T - t_{x^*}}{t_l}\right]^+$. Fourth, the optimal queuing time before production can be scheduled for machine maintenance or small machining projects to promote the efficient time utilization. Moreover, the decision criteria in selecting the optimal solution for the control of *MRR* are fully suggested in this paper; and the sensitivity analyses of the optimum solution are also provided. Furthermore, the simulated result of a real-world production planning presents good reliability of the *DMPC* Model in cost minimization. With this study, the production planning, production cost estimating, and even the contract negotiation can be then further approached.

The material removal rate is an important control factor of a machining project, and the control of machining rate is also critical for production planners. This study not only delivers the idea of automatic control on material removal rate to the modern machining technology, but also leads a machining project towards to achieve minimum cost. Future researches with the dynamic optimization modeling on multi-tool machining processes, multi-order machining control and scheduling, as well as the optimum design and implementation of PC-based *MRR* controllers on various types of *CNC* machines are encouraged. Thus, the foreseen future improvement to the work is definitely extended. In sum, the *DMPC* Model surely provides a better and practical solution to this field, and generates a reliable and applicable concept of machining control to the industry.

**Acknowledgment**

The authors would like to thank Mr. L. A. Yeh at AirTAC Corporation as well as the anonymous referees who kindly provide the suggestions and comments to improve this work.

**Appendix A:** The optimal solution for Situation 1.

Suppose that the material removal rate $x^{*'}(t)$ will never reach the upper limit $B$ before time $T$. Also, let $F = bx'^2(t) + cx(t) + c_s$.

From Euler Equation [2, 7], $F_x = \frac{d}{dt}F_{x'}$, it is derived that

$$c = \frac{d}{dt}2bx^{*'}(t).$$

There exists a constant $k_1$ to satisfy

$$x^{*'}(t) = \frac{c}{2b}t + k_1 \quad \forall t \in [t_{x^*}, T]. \tag{A1}$$

Integrating Eq. (A1) with $t$, it is obtained that

$$x^*(t) = \frac{c}{4b}t^2 + k_1 t + k_2 \quad \forall t \in [t_{x^*}, T]. \tag{A2}$$

With the transversality condition for free $t_x$ [2, 7], $F - x'F_{x'}|_{t_{x^*}} = 0$, then

$$cx^*(t_{x^*}) + c_s = bx^{*'^2}(t_{x^*}). \tag{A3}$$

Introducing the boundary condition, $x(t_x) = 0$, into Eq. (A3); it is derived that

$$x^{*'}(t_{x^*}) = \sqrt{\frac{c_s}{b}}. \tag{A4}$$

Comparing Eq. (A1) and (A4) at $t = t_{x^*}$, it is then found

$$k_1 = -\frac{c}{2b}t_{x^*} + \sqrt{\frac{c_s}{b}}. \tag{A5}$$

With Eq. (A2), (A5), and $x(t_{x^*}) = 0$; we have

$$k_2 = \frac{c}{4b}t_{x^*}^2 - \sqrt{\frac{c_s}{b}}t_{x^*}. \tag{A6}$$

Substituting Eq. (A5) and (A6) into Eq. (A1) and (A2); $x^{*'}(t)$ and $x^*(t)$ are then obtained.

Using the boundary condition, $x^*(T) = aQ$, $t_{x^*}$ is derived.

**Appendix B:** The optimal solution for Situation 2.

Before $x^{*'}(t)$ touches the upper limit, Eq. (1) and (2) are satisfied either. In addition, when it reaches the upper limit $B$; the Property is then applied.

Using the transversality condition for free end point $\tilde{t}$ [2, 7], $F - x'F_{x'}|_{\tilde{t}} = 0$; it is derived that

$$bx^{*'^2}(\tilde{t}) + cx^*(\tilde{t}) + c_s - x^{*'}(\tilde{t})2bx^{*'}(\tilde{t}) = 0. \tag{B1}$$

Introducing $x^{*'}(\tilde{t}) = B$ into Eq. (B1) and then compare with Eq. (2) at $t = \tilde{t}$, we have

$$x^*(\tilde{t}) = \frac{c}{4b}(\tilde{t} - t_{x^*})^2 + \sqrt{\frac{c_s}{b}}(\tilde{t} - t_{x^*}) = \frac{bB^2 - c_s}{c}. \tag{B2}$$

Using the boundary condition, $x^*(T) = aQ$, and Property; it is found that

$$\frac{bB^2 - c_s}{c} + (T - \tilde{t})B = aQ. \tag{B3}$$

By Eq. (B2) and (B3), $t_{x^*}$ and $\tilde{t}$ can be determined.

From Eq. (2), Property and $x^*(T) = aQ$; $x^*(t)$ is then obtained.

## References


[1] M. Balazinski and E. Ennajimi: Influence of feed variation on tool wear when milling stainless steel 17-4 Ph. *Journal of Engineering Industry*, **116** (1984) 516–520.

[2] A. Chiang: *Dynamic Optimization* (McGraw-Hill Inc, Singapore, 1992).

[3] S. K. Choudhury and I. V. K. Appa Rao: Optimization of cutting parameters for maximizing tool life. *International Journal of Machine Tool & Manufacture*, **39**-2 (1999) 343–353.

[4] E. P. DeGarmo, J. T. Black and R. A. Kohser: *Materials and Processes in Manufacturing* (Prentice Hall, New Jersey, 1997).

[5] K. H. Fuh, C. T. Chen and Y. F. Chang: Design and implementation for maximum metal removal-rate control of a constant turning-force system. *Journal of Materials Processing Technology*, **57** (1996) 351–359.

[6] J. Jung and A. Ahluwalia: Feature-based noncutting tool path selection. *Journal of Manufaturing Systems*, **13**-3 (1995) 165.

[7] M. Kamien and N. Schwartz: *Dynamic Optimization* (Elsevier Science Publishing, New York, 1991).

[8] T. Y. Kim, D. K. Choi, C. N. Chu and J. W. Kim: Indirect cutting force measurement by using servodrive current sensing and it's application to monitoring and control of machining process. *Journal of KSPE*, **13**-12 (1996) 133–145.

[9] T. Y. Kim and J. Kim: Adaptive cutting force control for a machining center by using direct cutting force measurement. *International Journal of Machine Tools and Manufacture*, **36**-8 (1996) 925–937.

[10] Y. Koren: *Computer Control of Manufacturing Systems* (McGraw Hill, New York, 1983).

[11] Y. Koren, T. R. Ko, K. Danai and A. G. Ulsoy: Frank wear estimation under varying cutting conditions. *ASME Journal of Dynamic Systems Measurement and Control*, **113** (1991) 300–307.

[12] K. S. Lee, L. C. Lee and S. C. Teo: On-line tool wear monitoring using a PC. *Journal of Materials Processing Technology*, **29** (1992) 3–13.

[13] Q. Meng, J. A. Arsecularatne and P. Mathew: Calculation of optimum cutting conditions for turning operations using a machining theory. *International Journal of Machine Tool & Manufacture*, **40** (2000) 1709–1733.

[14] D. C. Montgomery: *Design and Analysis of Experiments* (John Wiley & Sons, New York. 1976).

[15] A. Novak and H. Wilklund: On-line prediction of tool life. *Annals of CIRP*, **45**-1 (1996) 93–96.

[16] F. Rach and A. Rolstadas: Selection of optimum feed and speed in finish turning. *Annals of CIRP*, **54** (1971) 787–792.

[17] S. J. Rober and Y. C. Shin: Modeling and control of CNC machines using a PC-based open architecture controller. *Mechatronics*, **5**-4 (1995) 401–420.

[18] H. Soroush: Sequencing and due-date determination in the stochastic single machine problem with earliness and tardiness costs. *European Journal of Operational Research*, **113** (1999) 450–468.

[19] J. Wang and P. B. Luh: Scheduling of a machining center. *Mathematical Comput. Modelling*, **23** (1996) 203–214.

Chun-Hsiung Lan
90-2, Nanya W. Rd. Sec.2, Panchiao,
Taiwan 220, R.O.C.
E-mail: chlan@mail1.cc.tnit.edu.tw