VIRTUAL CNC MACHINING AND IMPLEMENTATION OF OPTIMUM MRR WITH TOOL LIFE CONTROL

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Key words: virtual manufacturing, material removal rate, electronic circuit, lathe control, human-machine interface.

ABSTRACT

The modeling of dynamic material removal rate (MRR) control and the optimum solution with tool life determination through Calculus of Variations to minimize the machining cost of an individual cutting tool under expected machining quantity are introduced in this paper. To analyse the cutting forces under the MRR optimization, the mathematical model is formulated by reverse experiments on an ECOCO PC-3807 CNC lathe, and the electronic circuit is developed through linear regression technique for virtual machining. The inaccuracy between actual voltage and simulated voltage is assured to be within 2%. By introducing the real-world CNC (computerized numerical control) machining case from AirTAC into the virtual system, the simulated cutting forces are shown to promise the feasible applicability of the optimum MRR control. Additionally, the implementation of the dynamic solution is experimentally performed on our proposed digital PC-based lathe system. The surface roughness of all machined work-pieces is found to not only stabilize as the tool consumed, but also accomplish the recognized standard for finish turning. This study not only provides the economical solution of virtual machining prior to realization for the optimum MRR, but also advances the realistic implementation through digital PC-based lathe system to the CNC machining industry with profound insight.

NOMENCLATURE

This paper is constructed on the basis of the following notations.

\[ a = \text{average volume of material machined per unit part.} \]
\[ B = \text{upper MRR limit.} \]
\[ bM'(t) = \text{marginal operation cost at } M'(t); \]
\[ \text{where } b \text{ is a constant.} \]
\[ bM'^2(t) = \text{operational cost at time } t. \]
\[ C_v = \text{transforming factor from voltage to cutting force.} \]
\[ c = \text{overall holding cost of unit chip per unit time.} \]
\[ c_l = \text{labor cost per unit time.} \]
\[ d = \text{depth of cut.} \]
\[ F_c = \text{cutting force.} \]
\[ F_v = \text{voltage of cutting force.} \]
\[ f = \text{feed rate.} \]
\[ K_s = \text{constant in the steady cutting force model.} \]
\[ M(t) = \text{cumulated volume of material machined at time } t. \]
\[ M'(t) = \text{MRR at time } t. \]
\[ O_b = \text{machining cost per tool for the dynamic machining model.} \]
\[ \overline{O}_b = \text{machining cost per tool for the traditional machining model.} \]
\[ p = \text{constant in the steady cutting force model.} \]
\[ Q = \text{expected machining quantity per unit tool.} \]
\[ T = \text{tool life for the dynamic machining model.} \]
\[ \overline{T} = \text{tool life for the traditional machining model.} \]
\[ t = \text{time for the optimum MRR to reach } B. \]

INTRODUCTION

Virtual reality (VR) is an emerging technology that aims at generating a perception of reality in a human subject, using devices that not only simulate more than one sense organ and a dynamic model of a real or fictitious environment [12] but also present complex plans to both experts and non-specialist [9, 15]. Due to the implementation by many industries for aviation, medical, and manufacturing and, in addition, latest experiences have shown, that the symbiosis of virtual reality techniques can work satisfactorily.

In recent years, a significant advance in CNC (computerized numerical control) machine tools has been made as high productivity factor in manufacturing processes. In a CNC system, the cutting tool is driven to a desired position with guaranteed accuracy and speed according to a programmed command. This brings increase in productivity, uniformity in machined parts, and less dependence on the experience and knowl-
edge of skilled machine operators. However, the CNC machine tool requires the NC programmer. In machining processes, the type of tool and the material of workpiece tend to change, and it is up to the NC programmer to choose the combination of feed rate and spindle speed. Conventionally, feed rate and spindle speed have been selected conservatively based on the worst machining conditions. In other words, they are inclined to be chosen at excessively low values with a view to prevent any physical damage or mechanical chattering of the CNC system, thus resulting in a lowering of machining efficiency.

Therefore, the address that the material removal rate (MRR) and the tool life are important control factors of machining operation [2, 7, 16] has been developed. As the MRR optimization under expected machining quantity for a single cutting tool is presented in the previous research [7], the attention to analyse cutting force economically has become necessary to the field. Since the virtual manufacturing (VM) is a kind of knowledge and computer-based system technology that integrates diverse manufacturing activities under a common umbrella, using VR technology [8], the interest to analyse the cutting forces prior to realization of the optimum MRR control through an electronic circuit is arising. To analyse the cutting forces under the MRR optimization by virtual machining, the electronic circuit is then developed through reverse experiments and linear regression techniques.

Additionally, many developments of PC-based machining systems have been in progress for the purpose of dynamic MRR control by manipulating feed-rate in accordance with constant depth of cut, a few of which are presented in this paper. Fuh et al. [4] have designed a variable structure system (VSS) controller on CNC turning machines. Rober and Shin [11] have also overridden the programmed feed-rate on the CNC milling machines as well as Kim and Kim [6] on the machining centers. Many case studies can also be found where adaptive control has been applied for the selection of optimal feed-rate [3, 10, 13, 14]. Although the basic objective of adaptive control is to maintain consistent performance of a system in the presence of uncertainty or unknown variation in plant parameters, these existing on-line control schemes are all considerably expensive and none is guaranteed to achieve the minimum machining cost.

As a way of command feed-rate transmission, most researches employed the method of driving servomotor directly to rotate the ball-screw shaft. Such method guaranteed continuous adjustment of feed-rate; nevertheless, it had been pronounced by some practical limitations. The CNC has an adjustment feed-rate manipulation in percentages of the programmed feed-rate, which is often done manually using a setting dial on the control panel. In order to apply the digital PC-based system to commercialized CNC machine tools without fixing the structure to a conventional CNC system, the interface between the digital PC-based control method and the CNC machines in a standardized manner is then proposed in this study.

The cost optimization of an individual cutting tool in machining operation has become important for CNC machining industry. In this paper, the mathematical modeling and optimum solution of the dynamic MRR control to minimize the machining cost of a cutting tool are introduced. The virtual machining to analyse the cutting force by the electronic circuit is well proposed and studied. The accuracy between the actual and simulated voltages is guaranteed to be more than 98%. By introducing a real-world CNC machining case, the simulated cutting forces are found to agree the achievability of the theoretical study. To realize the dynamic solution, the control scheme on a commercialized lathe system with DSP (Digital Processor Controller) and a man-machine interface are then developed. Moreover, the real-world industrial machining case is experimentally performed on our proposed digital PC-based lathe system. The surface roughness of all machined work-pieces is found to not only stabilize as the tool consumed, but also accomplish the recognized standard for finish turning. This study definitely contributes the economical technique for virtual machining under the optimum MRR as well as the advanced realization by the digital PC-based lathe system.

THEORETICAL BACKGROUND

In this paper, the mathematical modeling and solution of single-tool turning operation under expected machining quantity from the previous work are introduced and shown as below [7].

\[
\begin{align*}
\text{minimize} & \quad \int_0^T [bM'^2(t) + cM(t) + c_1] \, dt \\
\text{subject to} & \quad M(0) = 0 \\
& \quad M(T) = aQ \\
& \quad T \text{ is free} \\
& \quad 0 \leq M'(t) \leq B \\
& \quad \forall \ t \in [0, T]
\end{align*}
\]

Let \( M'(t) \) and \( T' \) be the optimal solution of the proposed model. There are two feasible cases [7].

1. **Situation 1:** \( M'(t) \) will not touch \( B \) before tool life \( T \).

With Euler Equation [1, 5], transversality condi-
tion for free horizon $T \; [1, 5]$, and boundary conditions; the optimum solution $[7]$ for *Situation 1* is derived as follows:

$$T^* = \frac{2\sqrt{b}}{c} \left( \sqrt{acQ + c_l - \sqrt{c_l}} \right)$$ (1)

$$M^* \left( t \right) = \frac{c}{2b} t + \sqrt{\frac{c_l}{b}} \quad 0 \leq t \leq T$$ (2)

$$M^* \left( t \right) = \frac{c}{4b} t^2 + \sqrt{\frac{c_l}{b}} t \quad 0 \leq t \leq T$$ (3)

Here, one property is proposed and discussed as follows:

**PROPERTY:** If $M^* \left( t \right)$ touches the line $B$, it will stay to be $B$ from the touch point $\tilde{t}$ to end point $T$.

*Proof:* From Eq.(2), $M^* \left( t \right)$ is a strictly increasing linear function of $t$. And it holds for the subinterval of $[0, \tilde{t}]$ subject to $0 \leq M^* \left( t \right) \leq B$. Since it cannot contradict Euler Equation $[1, 5]$ to be a decreasing function of $t$, the property is verified.

2. *Situation 2:* $M^* \left( t \right)$ will touch $B$ before tool life $T$.

Using the PROPERTY, transversality condition for free touch point $\tilde{t} \; [1, 5]$, and boundary conditions; the optimal solution $[7]$ for *Situation 2* is found as follows:

$$\tilde{t}^* = \frac{2b}{c} \left( B - \sqrt{\frac{c_l}{b}} \right)$$ (4)

$$T^* = \frac{1}{B} \left[ aQ - \frac{(bB^2 - c_l)}{c} \right] + \frac{2b}{c} \left( B - \sqrt{\frac{c_l}{b}} \right)$$ (5)

$$M^* \left( t \right) = \begin{cases} \frac{c}{2b} t + \sqrt{\frac{c_l}{b}} & \text{if } t \in [0, \tilde{t}] \\ B & \text{if } t \in (\tilde{t}, T] \end{cases}$$ (6)

$$M^* \left( t \right) = \begin{cases} \frac{c}{4b} t^2 + \sqrt{\frac{c_l}{b}} t & \text{if } t \in [0, \tilde{t}] \\ \frac{(bB^2 - c_l)}{c} + B(t - \tilde{t}) & \text{if } t \in (\tilde{t}, T] \end{cases}$$ (7)

3. Decision criteria

With Eq. (4) and Eq. (5), the two possible decision criteria $[7]$ are classified. They are

1. When $acQ \leq bB^2 - c_l$, the optimal solution is *Situation 1*.
2. When $acQ > bB^2 - c_l$, the optimal solution is *Situation 2*.

**ELECTRONIC CIRCUIT**

To analyse the cutting forces before implementation of optimum $MRR$ by virtual machining, the electronic circuit is developed through ECOKA PC-3807 CNC lathe with VERDURE PA-100 controller shown in Figure 1.

1. Reverse experiments

The Kistler-9001 force sensor is located into tool base of ECOKA PC-3807 CNC lathe as shown in Figure 2. Through the electronic charge amplifier of Kistler type 5007 to the AD/DA card of PCL-816 connecting to TATUNG TCS-5970W-200 PC, the measured forces are exactly collected.

The cylindrical part of SC45 is selected for the reverse experiments. Additionally, the TOSHIBA WTINR2020K16 tool holder and TNMG-160404 UX insert are also utilized for the experiments. Here, a measuring rod of $\phi 14 \times 700$ mm for constant cutting pressure from the turning tool is designed as shown in Figure 3. Through the enlarged acting forces, the calibration of the force-sensor equipped tool-base can then be achieved. The actual voltage is collected and recorded by the PC via the Direct Memory Access of AD card with a sampling rate of 100 KHz. The experiment is conducted every 5 kg from 15 kg to 100 kg, and the various combinations of different forces and voltages are then derived. By using the mean square method, the linear relation between force and voltage is composed.

![Fig. 1. Ecoka PC-3807 CNC lathe.](image-url)
and shown in Figure 4.

In this paper, the mathematical model of steady cutting force, $F_c = F_v + C_v = K_s \times d \times f^p$, is introduced. With the suggested feed rates of 0.2 mm/rev, 0.3 mm/rev, 0.4 mm/rev, the surface speeds of 150 m/min, 200 m/min, 250 m/min, and the cutting depth of 1 mm, 2 mm, 3 mm; there are twenty-seven S45C work-pieces of φ40 × 200 mm step-turned to the size shown in Figure 5. Through taking logarithm of the steady cutting force equation described above, the linear regression technique can then be applied to resolve the constants in this nonlinear model. The results are thus exponentially found to be $K_s = 440.5959$ and $p = 0.623658$. 

![Fig. 2. The tool base with force sensor.](image1)

![Fig. 3. The measuring rod.](image2)

![Fig. 4. Linear relation of force and voltage.](image3)
2. Electronic circuit development

Using the input voltages in the analogue circuit of extraction for square root and multiplying circuits under different cutting depth and feed rate to accomplish the simulating circuit; therefore, the design of voltage adjustable circuit is then employed. Since the value of cutting force $F_c$ is relatively large to be expressed by voltage, the inverting amplifying circuit is selected for the cutting force voltage $F_v$. Additionally, a subtract circuit is added to minimize as well as to guarantee the imprecision between actual and simulated voltages to be within 2%.

Moreover, the electronic circuit is connected to the PC through 8255 IC. With Dac0800 to manipulate the various voltages for the feed rate $f$ and cutting depth $d$. The voltage feedback is controlled by ADc0804 to decompose the output voltage of the circuit, and recorded into PC by 8255 IC. The AD/DA interface of the electronic circuit is then developed as shown in Figure 6.

VIRTUAL MACHINING

A numerical example from the real-world CNC industry in the previous study [4] is introduced to virtual machining for cutting force analysis. The machining process of a single-tool finishing turning operation of specific S45C fixture plates (see Figure 7) from AirTAC Corporation in Taiwan, R.O.C. is referenced for this study. All data compiled are transformed into SI units as well as US dollars and listed as follows:

$$Q = 40 \text{ parts}, \quad a = 17355 \text{ mm}^3, \quad b = 1.7 \times 10^{-8} \text{ (dollars-min)/mm}^6, \quad c = 6.625 \times 10^{-8} \text{ dollars/(min-mm}^3), \quad c_i = 0.135 \text{ dollars/min}, \quad B = 16470 \text{ mm}^3/\text{min}.$$

The optimum solution of Situation 1, the optimum tool life of 228.32 minutes, and the MRR variation of roughly 444 mm$^3$/min during the tool life are then calculated through a computer programme written in BORLAND C++ BUILDER (see Figure 8). It is observable that the production cost per unit tool of the proposed dynamic model is $56.21$ dollars less than the traditional machining model, which is considered cost competitive through years of experiences in AirTAC. However, the tool life determined for the dynamic model is 158.32 minutes longer than that in AirTAC's traditional machining model. This denotes that when the expected machining quantity $Q$ has satisfactory due-date allowance on the machining operation, the dynamic model can significantly minimize the machining cost for the individual tool.

For the purpose of virtual machining under dynamic MRR optimization, the Visual Basic 6.0 is se-
lected to develop the interface programme. In this simulation, the feed rate and depth of cut are selected as 0.08 mm/rev and 0.35 mm respectively. The simulated result from the proposed electronic circuit for ECOCA PC-3807 is shown as Figure 9. It is found that the cutting force tends to be stabilized at 27 Newtons, which is considered low enough to maintain the well-finished surface roughness without chattering. Therefore, the MRR optimization is deemed to be applicable to the CNC machining industry.

IMPLEMENTATION

1. The digital lathe system

The experimental setup of the digital lathe system via PC-based control for realization of the optimum MRR control through the human-machine interface controller is shown in Figure 10. The digital lathe system consists of four components. The characteristics of each component are described as below:

1) The user interface provides programs with the following functions:
   - Generation of desired reference input and calculation of the feedback information generated from the commanded input for the feed actuator servo systems.
   - Providing the parameter setting of spindle motor system due to the theoretical development.

2) The networking provides communications protocol programs with the following functions:
   - Modbus, the industrial communication network equipment, generally consists of one master side and many slave side maneuvers by a specific address. In the process of communication operation, the master side delivers a serial command signals to the slave side and wait to receive feedback signals from the slave side after the following command is provided. The slave side obtains the request signal for a start to verify the assigned number with its address number, and the master side demands to deliver the data signal with the assigned number correctly. In other words, if there is error messing in the communication process, the slave...
side does not deliver any returned pass corresponding data to master side and send a messing error to check the mistakes instead.

Generally, the Modbus has two parts: \textit{RTU} and \textit{ASCII} modules. \textit{RTU} module supports the two data format in Boolean and 16 bit unsigned integer and it is used to cope with large data material by big-endian. The errors examine adopted \textit{CRC} (Cyclical Redundancy Check) in communication format. In this paper, the \textit{ASCII} module is used in less quantity with character format communication and \textit{LRC} (Longitudinal Redundancy Check) in errors examine.

(3) The digital Lathe control scheme for maneuvering the cutting has the following characteristics:

A servo motor with screw gears for driving the cutting tool base in the feed directions, and the frequency transformer with induced motor manipulated for the spindle rate via 232-485 converter by the PC-based are included in the proposed lathe re-equip system.

The Pmc32-6000 motion control card supports the pulse output. There is only one output signal wired for each channel, and the card also supports quadrature encoder which encodes the position of the spindle shaft of the motors for encoding, pulse/direction counting or up/down counting.

2. The man-machine interface

A digital-signal-processor-based board was developed to perform the required computations in real time, which is called the Digital Signal Processor (\textit{DSP}). The PMC32-6000 \textit{DSP}-based motion control card was designed to provide a powerful computation process. A \textit{TI}'s code composer to develop and debug the \textit{DSP} hardware is applied, and the \textit{NI}'s Labview is selected as the interface. The \textsc{MATLAB} is utilized to plot the experimental results. According to the experimental data, the control and compensate strategy is thus analyzed, revised, and evaluated. The \textit{DSP} processor on the mother board is a TMS320C31 with 1 Mbyte of SRAM. The mother board has eight independent analog-to-digital converters (each with 12-bit resolution) with a programmable sampling frequency up to 50 KHz. The unique architecture is designed so that when the instant the sampling interrupt occurs, all eight input values have been converted and can be read simultaneously by all \textit{DSPs}. The Pmc32-6000 has six totally independent analog output ports, each with 12-bit resolution. In this manner, the computation and communication power can be tailored to individual applications.

The window man-machine programming interface providing the operator to set machining parameters of the turning process in the spindle rate as well as the feed forward speed is shown in Figure 11, and the window of the programmed human-machine interface written by \textsc{BORLAND C++ BUILDER} is shown in Figure 12.

RESULTS AND DISCUSSION

In this study, a desk-top lathe control system is established, the federate is generated by the servo-drive which controls the servo-motor, and the spindle speed is controlled by the inverter.

The φ25 mm × 180 mm S45C work-pieces are selected for the experiment, and the length of turn for each work-piece is determined to be 150 mm. The spindle speed is ranged from 712 rpm to 826 rpm, and the feed rate and depth of cut are selected as 0.08 mm/rev and 0.35 mm respectively. The surface roughness of
all finished work-pieces is measured at the front, middle, and rear regions on the MITSUTOYO measuring instrument SURFTEST SV-400 as shown in Figure 13. The surface roughness of all ninety-eight finished work-pieces under the digital lathe system is plotted as Figure 14.

It can be seen from Figure 14 that the surface roughness tends to increase as the tool life is consumed. However, the growing rate of surface roughness decelerates and stabilizes as the tool life consumed. Besides, it is also found that the surface roughness of machined work-pieces is found to be within 2.9 μm which satisfactorily matches the recognized standard for finish turning. With the experimental result, the adaptability and applicability of the dynamic machining model are guaranteed.

**CONCLUDING REMARKS**

In recent years, a significant progress in CNC machine tools has been made as high productivity factor in the manufacturing operations. The material removal rate (MRR) is an important control factor of machining operation, and the tool life is also a critical parameter of machining process. The mathematical modeling of optimum MRR and tool life determination through Calculus of Variations to minimize the machining cost of a cutting tool under expected machining quantity are introduced in this paper.

For analysing cutting forces before implementation, the electronic circuit from reverse experiments is well developed for virtual machining. The accuracy between actual voltage and simulated voltage is guaranteed to be more than 98%. By analyzing the cutting force of a real-world case from AirTAC, the simulated cutting force is found to promise the surface roughness as well as the applicability of the optimum MRR control. To realize the dynamic MRR control, the implementation is moreover experimentally functioned on a digital controlled PC-based lathe system. It is shown that the machined parts are all within a surface roughness of 2.9 μm. This paper definitely not only contributes the economical approach for virtual machining, but also develops the realization of digital PC-based lathe system for the optimum MRR with profound insight.

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