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Sliding mode cutting force regulator for turning processes

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Abstract

Continuous sliding mode control is applied to turning processes for cutting force regulation. The motivation of the use of the slide mode control scheme is to solve the nonlinearity problem caused by the feedrate override command element in the commercial CNC machine tool. When the adaptive control algorithm is applied to the commercial CNC machine tool, it is one of the practical methods that the programmed feedrate is overridden after the control algorithm is carried out. However, most CNC lathe manufacturers offer limited number of data bits for feedrate override, thus resulting in nonlinear behavior of the machine tools. Such nonlinearity brings 'quantized' or discrete effect so that the optimal feedrate is rounded off before being fed into the CNC system. To compensate for this problem, continuous sliding mode control is applied. Simulation and experimental results are presented in comparison with those obtained from applying adaptive control which is a widely used approach in cutting force regulation. Adaptive control loses its effectiveness in the presence of nonlinearity since it generally requires linear parametrization of the control law or the system dynamics. Experiments are conducted under various machining conditions, subject to changes in spindle speed, material of work-piece, and type of machining process. The suggested slide mode controller shows smoother cutting force fluctuation, which cannot be achieved by the conventional adaptive controller. The experimental set-up reflects the emphasis on the practicality of the sliding mode controller. In order to avoid the use of a dynamometer in the course of measuring the cutting force, the indirect cutting force measuring system is used by means of feed drive servo-motor current sensing. © 1998 Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

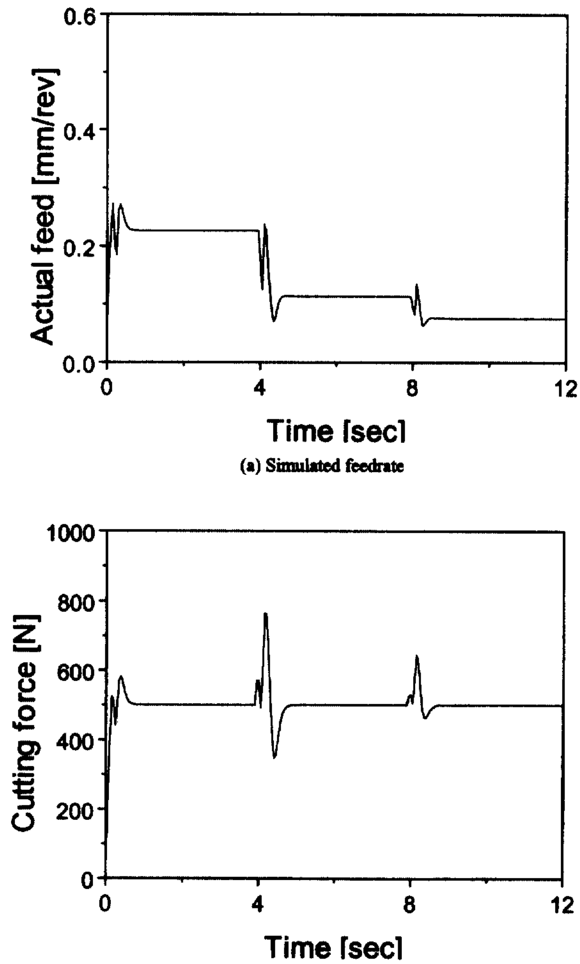
In recent years, a significant advance in CNC machine tools has been made as high productivity and precision emerged as important factors in manufacturing processes. In a CNC system, the cutting tool is driven to a desired position with guaranteed accuracy and speed according to a programmed command. This brings increase in productivity, uniformity in machined parts, and less dependence on the experience and knowledge of skilled machine operators. However, the CNC machine tool requires the NC programmer. In machining processes, the type of tool and the material of work-piece tend to change, and it is up to the NC programmer to choose the combination of feedrate and spindle speed. Conventionally, feedrate 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.

For this reason, the development of an adaptive controller has been in progress for the purpose of regulating cutting force by maximizing feedrate in accordance with constantly changing depth of cut. Many case studies can be found where adaptive control has been applied for the selection of optimal feedrate [1–5]. Generally, 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. Since machining conditions tend to vary, adaptive control is appropriate for machining processes.

As a way of command feedrate transmission, most of the past studies employed the method of using voltage input to drive the servo-motor directly and, in turn, to rotate the ballscrew shaft. Such a method guaranteed continuous adjustment of feedrate, but it had been marked by some practical limitations. In order to apply adaptive control theory to commercialized CNC machine tools without modifying the structure of conventional CNCs, a way to interface the adaptive control system and the CNC in a standardized manner is in progress. The CNC has a feedrate override circuit which allows the adjustment of feedrate in percentages of the programmed feedrate, often done manually using a dial on the control panel.

A modified method of overriding the feedrate by a computer is being introduced. Lauderbaugh and Ulsoy introduced the method of overriding programmed feedrate with a voltage from the digital-to-analog converter (DAC) of the control computer, which took place in the analog circuitry that generated the pulse train to the stepping motor [6,7]. This scheme was further developed by Kim, who devised a command feedrate transmission system with standard interface between a control computer and the CNC of a machining center [8]. A wide range of feedrate override (typically from 0 to 255%, every 1%), which is applied for adaptive cutting force regulation for CNC milling process, is used. It had proved to be successful for a commercialized CNC machine tool, in which up to eight parallel signals can be transmitted to the programmable machine controller (PMC) of the CNC simultaneously, allowing feedrate override from 0 to 255%. However, in many other machine tools currently used in the industry, only four points are available for external device connection, meaning the feedrate can be increased or decreased in 16 steps, normally ranging from 0 to 150%, every 10%. Therefore, the limitation on the number of signal bits results in the 'quantized' or discrete effect so that the optimal feedrate is rounded off before being fed into the CNC system. This brings up the problem of the nonlinear behavior of the CNC system.

The simulation results presented in Fig. 1 and Fig. 2 clearly show the effect of the four-bit feedrate override command when adaptive control is applied. For both cases, the reference force,



(a) Simulated feedrate

(b) Simulated cutting force

Fig. 1. Simulated adaptive control system response by using the eight-bit feedrate override command. (Reference force: 500 N; programmed feedrate: 0.2 mm/rev; spindle speed: 600 rpm, steel.)

the programmed feedrate, and the spindle speed are assumed to be 500 N, 0.2 mm/rev, and 600 rpm, respectively. Each simulation runs for 12 s, and the depth of cut increases by 1 mm from 1 to 3 mm every 4 s. As in Fig. 1, when the system allows a wide range of feedrate override with a small unit, namely from 0 to 255% in units of 1%, the cutting force is regulated at the reference value with zero steady-state error. On the contrary, when the system takes the four-bit feedrate override command into consideration as in Fig. 2, the cutting force fluctuates considerably. Large fluctuation poses critical problems in machining processes because it may bring poor surface finish and tool breakage.

One solution to control a CNC lathe system having such a nonlinear element is sliding mode control which is based on the variable structure system theory. The sliding mode control method-

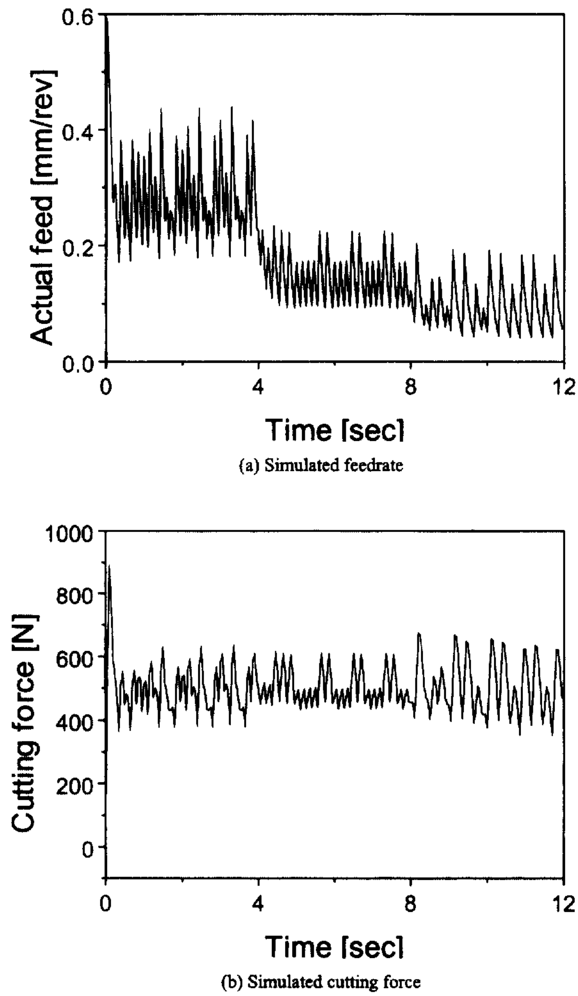


Fig. 2. Simulated adaptive control system response by using the four-bit feedrate override command. (Reference force: 500 N; programmed feedrate: 0.2 mm/rev; spindle speed: 600 rpm, steel.)

ology has been developed and applied to the control of robot manipulators, motors, automotive engines, and aircraft until Chang and Chen added the category of machining process to the list [9].

Chang and Chen [9] proposed a new variable structure system approach to adjust controller gain according to the sliding mode with high robustness in order to stabilize the constant turning force adaptive control against nonlinear time-varying gain perturbation in cutting processes. Hwang and Chen extended the sliding mode control methodology into a discrete-time form to combine with parameter estimation having a variable forgetting factor to stabilize the turning system against variable gain and unmodeled dynamics [10]. In addition, Luo and Zhang verified the advantages of sliding mode control, such as improvements in system performance and feasibility for real-time implementation, from their application of the control technique to a CNC lathe system [11]. However, it is noteworthy that most of the aforementioned applications of sliding mode control methodology were validated by simulations only. In this respect, thorough investigations in experimental verification are yet to be accomplished.

For this reason, a sliding mode controller, which is practically applicable to the conventional CNC machine tool having a nonlinear four-bit feedrate command element, is proposed and verified with a series of experimental works in this paper. On the other hand, to achieve the practical applicability to the commercialized CNC, an indirect cutting force measurement by servo motor current sensing is utilized without a supplementary measuring instrument, such as a dynamometer (for details, refer to Kim [8]).

2. Sliding mode controller for cutting force regulation

A sliding mode controller is suggested for cutting force regulation in the turning process which has the data bit limitation of the feedrate override command. The control scheme is also verified by the simulation study.

2.1. Modeling of cutting process and CNC servo systems

The block diagram of the force feedback system is shown in Fig. 3. It is a sampled data feedback loop where the feedrate v_a adapts itself to the actual cutting force F_c according to changes in machining conditions as cutting proceeds. Immediately after it is sampled, the actual cutting force F_c is compared with a predetermined reference force F_{ref}. The difference between F_c and F_{ref} is the error, which is used as an input to the sliding mode controller. The control system consists of the cutting process, the CNC servo system, the four-bit feedrate override command element, and the sliding mode controller. The plant to be controlled includes the cutting process and the CNC servo system. The machine tool to be dealt with throughout the study is a typical conventional CNC lathe controlled by a CNC whose model name is FANUC 0-T. The FANUC 0-T CNC has four PMC (Programmable Machine Controller) points available and allows only four-bit feedrate override commands ranging from 0 to 150% at every 10%.

The cutting process and the CNC servo system model can be represented as

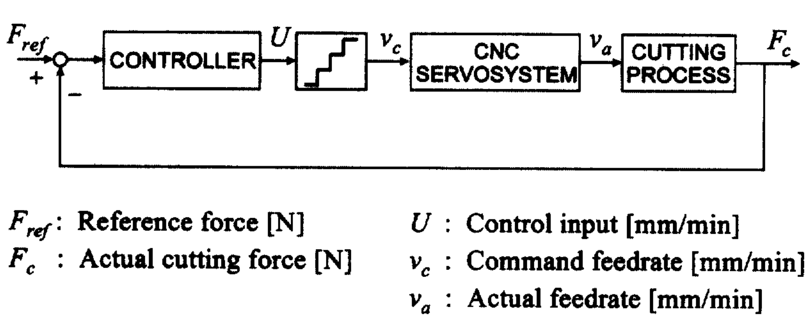


Fig. 3. Block diagram of the force feedback control system.

$$G_p(s) = \frac{F_c(s)}{v_a(s)} = \frac{1}{N}\frac{K_s d}{1 + \tau_c s}, \tag{1}$$

$$G_s(s) = \frac{v_a(s)}{v_c(s)} = \frac{1}{1 + \tau_s s}, \tag{2}$$

where N is the spindle speed in rpm, K_s is the specific cutting force in N/mm^2, d is the depth of cut, τ_c is the time constant of the cutting process, and τ_s is the time constant of the CNC servo system. Figure 4 shows the step response of the CNC system used in this paper. The programmed feedrate is overridden from 10 to 150%, and the time to reach 0.632 of the step input is found graphically. The time constant τ_s is measured to be 0.17 s.

2.2. *Sliding mode control scheme for cutting force regulation*

Sliding mode control is appropriate for the control of nonlinear systems in the presence of modeling imprecision, which may result from actual uncertainty about the plant or from the choice of a simplified representation of the system's dynamics. For the class of systems to which it is applied, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance. Sliding mode control is based on the variable structure system theory, which allows the control to change its structure, that is, to switch at any instant from one to another member of a set of possible continuous functions of the state. The sliding mode controller design problem is then to select the parameters of each control structure and to define the switching logic.

In order to apply the sliding mode control methodology to a turning process, the following equations are obtained from the dynamic Eqs (1) and (2):

$$\dot{F}_c(t) = -\frac{1}{\tau_c}F_c(t) + \frac{K_s d}{\tau_c N}v_a(t), \tag{3}$$

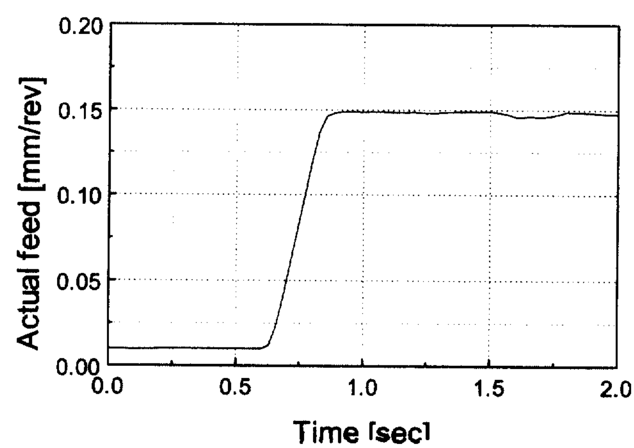


Fig. 4. Step response of the z-axis feed drive system.

$$\dot{v}_a(t) = -\frac{1}{\tau_s} v_a(t) + \frac{1}{\tau_s} v_c(t). \tag{4}$$

Combining Eqs (3) and (4) eliminates $v_a(t)$, thus resulting in the second order system.

$$\ddot{F}_c(t) = a_1 F_c(t) + a_2 \dot{F}_c(t) + b(t) v_c(t), \tag{5}$$

where

$$a_1 = -\frac{1}{\tau_s \tau_c}, \; a_2 = -\frac{\tau_s + \tau_c}{\tau_s \tau_c}, \; b(t) = \frac{K_s d}{\tau_s \tau_c N}.$$

Assuming the spindle speed remains the same throughout the machining process, a_1 and a_2 remain constant as well while the control input $b(t)$ varies with time. Let the state vector be $\mathbf{F}_c = [F_c \; \dot{F}_c]^T$. The control problem is to get the state $\mathbf{F}_c$ to track $\mathbf{F}_{ref} = [F_{ref} \dot{F}_{ref}]^T$, where F_{ref} is the reference cutting force and $\dot{F}_{ref}$ is apparently zero.

Eq. (5) can be rewritten in a more generalized form as follows:

$$\ddot{F}_c(t) = f(F_c(t), \dot{F}_c(t)) + b(t) v_c(t), \tag{6}$$

where $v_c(t)$ can be regarded as the control input. $K_s d$ typically ranges from 0 to 2000 N/mm for turning [12], and accordingly $b(t)$ verifies

$$b_{\min} \le b \le b_{\max}. \tag{7}$$

Since the control input enters multiplicatively in the dynamics, it is natural to choose our estimate $\hat{b}$ as the geometric mean of the bounds in Eq. (7).

$$\hat{b} = (b_{\min} b_{\max})^{1/2}. \tag{8}$$

Let the tracking error e and the sliding surface $s = 0$ be defined as in Eqs (9) and (10), respectively:

$$e = F_c - F_{ref}, \tag{9}$$

$$s = \left(\frac{\mathrm{d}}{\mathrm{d}t} + \lambda\right) e = \dot{e} + \lambda e, \tag{10}$$

where λ is a positive constant.

Differentiating s with respect to time and substituting Eq. (6) and Eq. (9) gives

$$\dot{s} = f + b v_c - \ddot{F}_{ref} + \lambda \dot{e}. \tag{11}$$

Then the control law that would achieve $\dot{s} = 0$ can be chosen as

$$v_c = \hat{b}^{-1}\{-f + \ddot{F}_{ref} - \lambda \dot{e} - K\,sgn(s)\}, \tag{12}$$

where sgn is the sign function defined as

$$sgn(s) = \begin{cases} +1 & \text{if } s > 0 \\ 0 & \text{if } s = 0 \\ -1 & \text{if } s < 0 \end{cases} \tag{13}$$

The last term in Eq. (12) accounts for the switching logic inherent in sliding mode control.

The problem is narrowed down to determining the control discontinuity gain K. It is selected to satisfy the sliding condition as following:

$$\begin{aligned}\frac{1}{2}\frac{d}{dt}s^2 = s\dot{s} &= [f + b\hat{b}^{-1}\{-f + \ddot{F}_{ref} - \lambda\dot{e} - K\,sgn(s)\} - \ddot{F}_{ref} + \lambda\dot{e}]s \\ &= [(1 - b\hat{b}^{-1})(f - \ddot{F}_{ref} + \lambda\dot{e}) - b\hat{b}^{-1}K\,sgn(s)]s \\ &\leq |1 - b\hat{b}^{-1}|\cdot|f - \ddot{F}_{ref} + \lambda\dot{e}|\cdot|s| - b\hat{b}^{-1}K|s| \leq -\eta|s|,\end{aligned} \tag{14}$$

where, η is a positive constant. It essentially requires that the squared distance to the surface s^2 decreases along all trajectories. It constrains trajectories to be attracted towards the sliding surface.

Therefore K must verify

$$K \geq |\hat{b}b^{-1} - 1|\cdot|f - \ddot{F}_{ref} + \lambda\dot{e}| + \hat{b}b^{-1}\eta. \tag{15}$$

Since, $\dot{F}_{ref} = \ddot{F}_{ref} = 0$,

$$K = |\hat{b}b^{-1} - 1|\cdot|f + \lambda\dot{F}_c| + \hat{b}b^{-1}\eta, \tag{16}$$

where b is chosen to be b_{min} such that condition (15) is always guaranteed. Accordingly, the command feedrate Eq. (12) can be simplified as

$$v_c = \hat{b}^{-1}\{-f - \lambda\dot{F}_c - K\,sgn(s)\}. \tag{17}$$

There are infinitely many possible values for K. However, K must not be chosen too conservatively, that is, it must not be excessively large because large K results in large control input.

On the other hand, in order to account for the presence of modeling imprecision and of disturbances, the control law has to be discontinuous across the sliding surface. This discontinuity leads to chattering which involves high control activity and further may excite high frequency dynamics neglected in the course of modeling. The chattering can be eliminated by smoothing out the control discontinuity in a thin boundary layer neighboring the sliding surface as illustrated in Fig. 5. In the figure, Φ is the boundary layer thickness, and ϵ is the boundary layer width, which is equivalent to the allowed tracking error. Bounds on s can be interpreted as bounds on the tracking error vector, and the scalar s represents a true measure of tracking performance. This can be expressed in a compact symbolic form as

$$\forall t \geq 0,\ |s(t)| \leq \Phi,\ \mathbf{x}(0) = \mathbf{0} \Rightarrow \forall t \geq 0,\ |\tilde{x}^{(i)}(t)| \leq (2\lambda)^i\epsilon,\ i = 0,\ldots,n-1, \tag{18}$$

where $\epsilon = \Phi/\lambda^{n-1}$ and n is the order of a system.

Outside the boundary layer, the control law is chosen to satisfy the sliding condition (14), which guarantees that the boundary layer is attractive. On the other hand, all trajectories starting inside the boundary layer remain inside it for all $t \geq 0$. Then the control law is interpolated inside the boundary layer. This leads to tracking to within a guaranteed precision ϵ, rather than perfect tracking.

Continuous sliding mode control can be achieved simply by replacing the sign function in Eq. (17) with a saturation function defined as

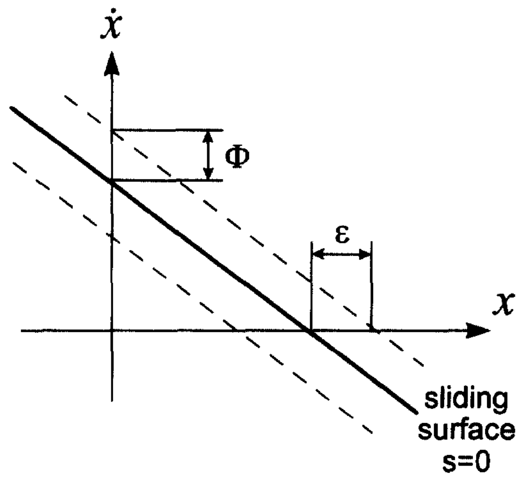


Fig. 5. The boundary layer for the slide mode controller.

$$sat(x) = \begin{cases} x & \text{if } |x| \leq 1 \\ sgn(x) & \text{otherwise} \end{cases} \tag{19}$$

Therefore, the command feedrate can be modified as

$$v_c = \hat{b}^{-1}\{-f - \lambda\dot{F}_c - K\,sat(s/\Phi)\}. \tag{20}$$

The smoothing of control discontinuity inside the boundary layer essentially assigns a low-pass filter structure to the local dynamics of the variable s. Therefore, the control law can be tuned up so as to achieve a trade-off between tracking precision and robustness to unmodeled dynamics.

2.3. Simulation results

Continuous sliding mode control is applied to a turning process and is verified by simulation. The reference force is selected to be 500 N, and the allowed tracking error is guaranteed to be smaller than 5% of the reference force, namely 25 N. Since the system being dealt with is a second order system, Φ is simply

$$\Phi = \epsilon\lambda. \tag{21}$$

The programmed feed is 0.2 mm/rev, thus allowing the feed to be overridden from 0 to 0.3 mm/rev. The control sampling period is chosen to be 10 ms. In the cutting process model, the spindle speed is set at 600 rpm, and the depth of cut undergoes step changes from 1 to 3 mm by increments of 1 mm, as illustrated in Fig. 6. The total simulation time is 12 s.

Now the problem of choosing sliding surface parameters λ and η remains. System performance is especially sensitive to control bandwidth λ since it accounts for the unmodeled part of the system dynamics. Although the tuning of this scalar may in practice be done experimentally, considerable insight on the overall design can be obtained by explicitly analyzing the various factors limiting λ. In mechanical systems, λ is typically limited by the following factors [13]:

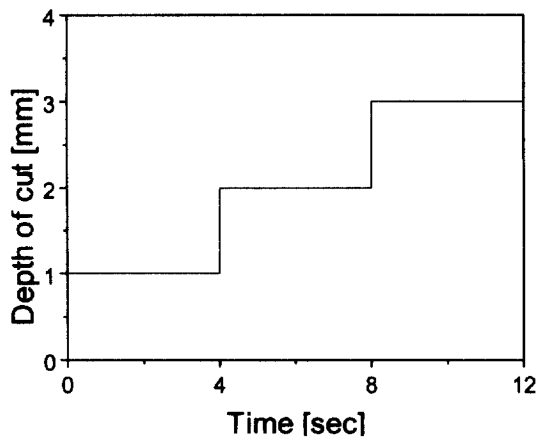


Fig. 6. Step changes in depth of cut.

1. λ must be smaller than the frequency v_R of the lowest unmodeled structural resonant mode, or

$$\lambda \leq \frac{2\pi}{3} v_R; \tag{22}$$

2. λ must account for neglected time delays, or

$$\lambda \leq \frac{1}{3T_A}, \tag{23}$$

where T_A is the largest unmodeled time-delay;

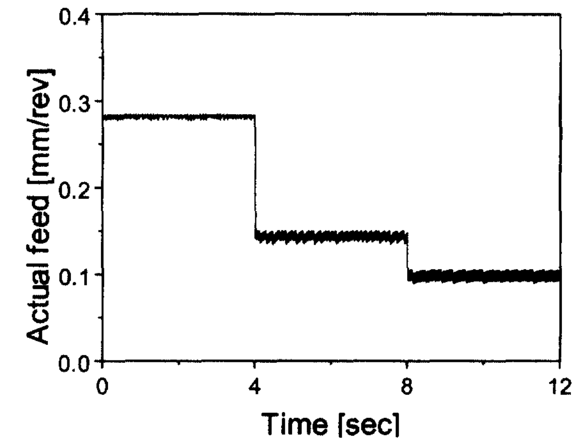
3. λ must be limited by a full-period processing delay, or

$$\lambda \leq \frac{1}{5} v_{\text{sampling}}, \tag{24}$$

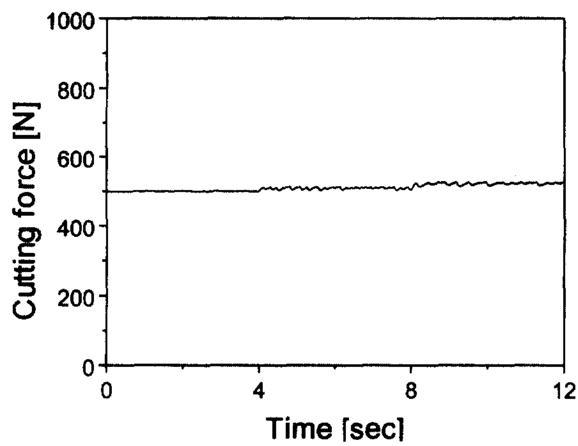
where v_{sampling} is the sampling rate.

The desired control bandwidth λ is the minimum of the three bounds in (1), (2) and (3). Bound (22) essentially depends on the system's mechanical properties, while the bound (23) reflects limitations on the actuators, and the bound (24) accounts for the available computing power. In this paper, λ and η are selected to be 20 Hz and 0.1, respectively.

Figures 7 and 8 show the tracking performances of the sliding mode controller in the absence and presence of the four-bit feedrate override command, respectively. Compared with Fig. 2 where adaptive control is applied, Fig. 8 indicates that the average tracking error has been reduced from 61.9 to 8.9 N. More importantly, the transient response has improved, including a reduction in overshoot. However, in Fig. 8, chattering in the range of about 17 N can be detected, which arises in the selection of the boundary layer thickness Φ. The value of Φ is, in turn, affected by the precision ϵ. Thus, if Φ is selected too small, the control input is chosen according to the switching logic, which results in chattering. On the contrary, if Φ is selected large enough, chattering is



(a) Simulated feedrate



(b) Simulated cutting force

Fig. 7. Simulated sliding mode control system response with the ideal continuous feedrate override command.

suppressed at the cost of the tracking error. Comparing Fig. 7 and Fig. 8 suggests that sliding mode control makes the system insensitive to the types of the feedrate override command. In both cases, the feeds are reduced at the points of step changes in depth of cut, thus regulating the cutting forces.

3. Experimental set-up

A schematic diagram of the experimental set-up is illustrated in Fig. 9. The overall experimental set-up consists of a commercialized CNC lathe, a servo-motor current sensing system for indirect cutting force measurement, and a command feedrate transmission system. The CNC lathe PUMA 6J manufactured and commercialized by Daewoo Heavy Industries Company is utilized as the

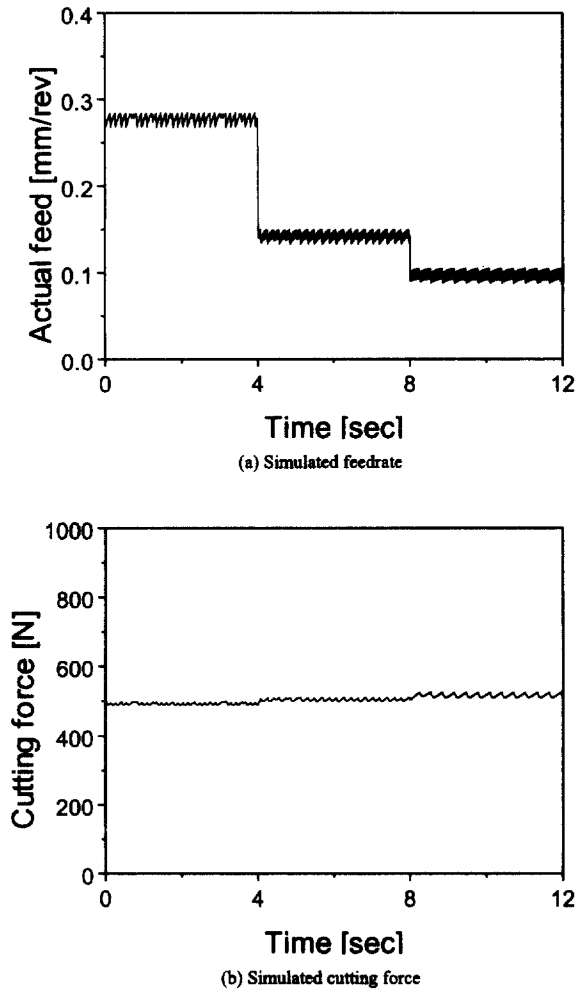


Fig. 8. Simulated sliding mode control system response with the discrete feedrate override command.

machine tool. Equipped with FANUC CNC 0-T, the CNC lathe is interfaced with an IBM compatible PC with a built-in Intel 80486 microprocessor. The interface is designed to allow PUMA 6J to be under digital control implemented in the PC. The sliding mode control algorithm is coded in the C language.

Hall sensors are used to sense the u- and v-phase input currents into the z-axis servo-motor. Since the feed force has been chosen to be controlled, input currents into the x-axis servo-motor and the spindle motor need not be measured. The changing cutting force during machining acts as a load torque to the feed system and reflects the changes in the servo-motor current. The actual feedrate is not directly used in the control algorithm, but it needs to be measured in order to monitor its behavior. This is done by detecting the angular displacement of the rotor of the servo-motor. The encoder, which is directly attached to a 12-mm-pitch ball screw, emits 2000 pulses per revolution of the shaft.

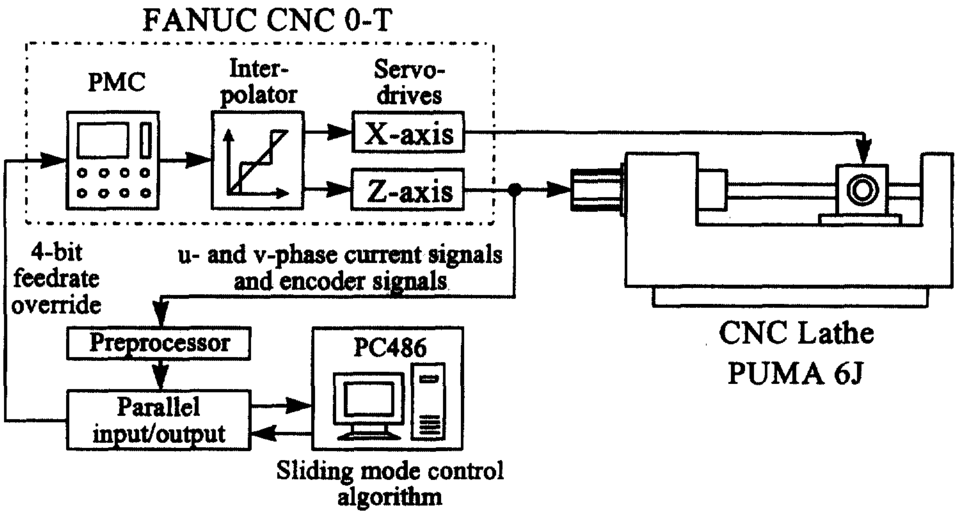


Fig. 9. Schematic diagram of the experimental set-up.

The acquired *u*- and *v*-phase current signals and encoder signals are fed into a preprocessor, where the former are *d–q*-transformed and the latter are counted such that they are converted to readily usable values in the control algorithm. The *d–q* coordinate is a moving coordinate fixed on the rotor of the servo-motor, which yields a DC value proportional to the driving torque by means of coordinate transformation [8]. The features of the preprocessor include analog-to-digital conversion, *d–q* transformation, and low-pass filtering.

The command feedrate calculated from the sliding mode control algorithm is converted to a percentage of the programmed feedrate. Since only four binary digits are available for expressing the percentage, the range of the command feedrate is limited from 0 to 150% of the programmed feedrate. The feedrate override in the form of binary digits is transmitted to the PMC of the CNC.

Naturally a dynamometer is by far the best device for force measurement in machining in terms of accuracy and disturbance rejection. However, the dynamometer is not suitable in a practical sense in the aspects of cost, installation difficulties, and restrictions on coolant supply. As an alternative measure, the method of servo-motor current sensing has been suggested.

However, the current includes friction in sliding carriage unit because lubrication is not always uniform. Friction is marked by nonlinearity, but experiments show that it tends to increase inversely as feedrate. The relation between frictional force (or its equivalence in amperes) and feedrate is approximated to be quadratic as follows:

$$I_{\text{fric}} = a(v_a - v_{a,min})^2 + b, \tag{25}$$

where I_{fric} = servo-motor current equivalence of frictional force in amperes

$$a = (I_{\text{fric, max}} - I_{\text{fric, min}})/(v_{a,\text{max}} - v_{a,\text{min}})^2,$$

$$b = I_{\text{fric, min}}.$$

The subscripts ‘max’ and ‘min’ denote maximum and minimum feedrates, respectively. Since the frictional force varies with temperature, lubrication, and the type of machine tool, it is suggested that the coefficients a and b be constantly updated before the control algorithm is applied. During machining subject to sliding mode control, I_{fric} is subtracted from the sampled feedback servo-motor current, thus compensating the frictional force.

In order to verify the linear relation between the servo-motor current and the cutting force, the two quantities are measured simultaneously during machining. The material used is SM45C steel, with depth of cut and spindle speed fixed at 1 mm and 600 rpm, respectively. The feed is varied from 0.03 to 0.45 mm/rev, every 0.06 mm/rev. At each value of the feed, the servo-motor current I_q (with friction compensated) and the actual cutting force F_c are sampled at the frequency of 1 kHz. The cutting force signal is measured by a piezoelectric table dynamometer. The resulting data are plotted in Fig. 10, and the problem can be treated as a linear regression problem, which leads to the following linear equation:

$$I_q = -0.12432 + 0.00629F_c. \tag{26}$$

Eq. (26) implies that 1 A of servo-motor current is approximately equivalent to 145 N of cutting force.

4. On-line cutting force regulation experiment

The performance of the suggested sliding mode controller has been verified by a series of experimental works under various cutting conditions. It has been conducted in the presence of plant nonlinearity caused by the four-bit feedrate override command element. The first experimental results are shown in Fig. 11. The work-piece material is 1024 steel, and the depth of cut changes stepwise from 1.0 to 2.0 mm. The spindle speed is 600 rpm and the programmed feed is 0.1 mm/rev. The sliding surface parameters are chosen to be $\lambda = 20$, $\eta = 1$. The reference force is preset at 100 N, and the allowed error is selected to be 10 N. As a result, the average tracking error is contained within 8.3 N, and at the instant of depth increase, the feed drops at a rapid rate, thus keeping the cutting force within the desired range.

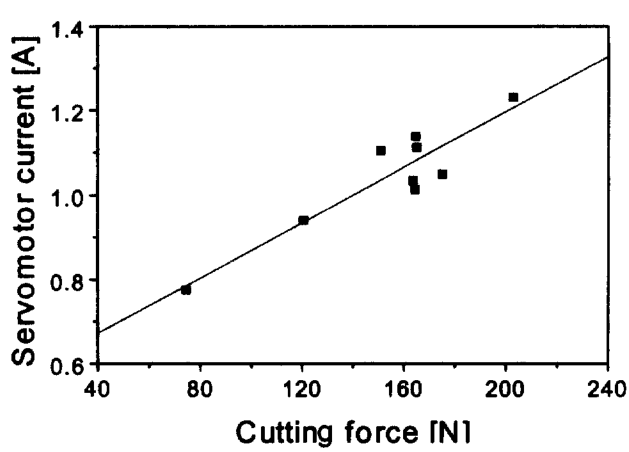
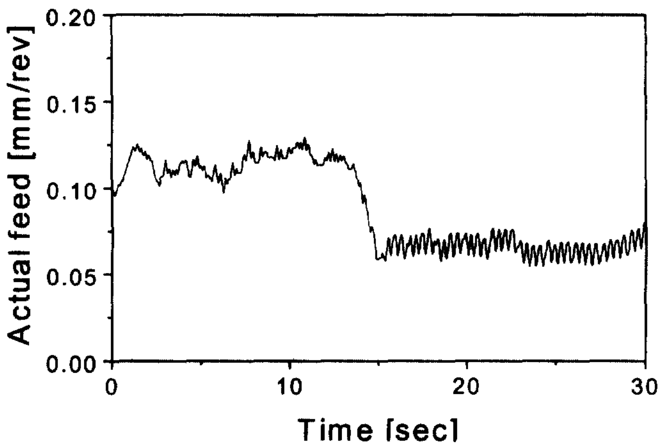
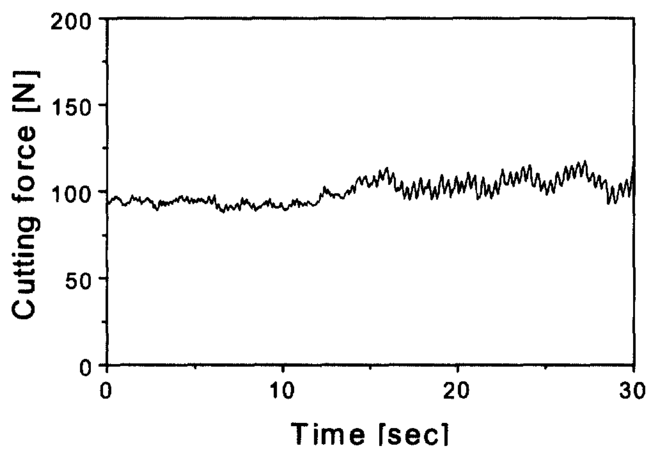


Fig. 10. Static characteristics of the indirect cutting force measurement system.



(a) Actual feedrate



(b) Regulated cutting force

Fig. 11. Sliding mode control system response by using the four-bit feedrate override element. (Work-piece material: 1024 steel; depth of cut: from 1.0 to 2.0 mm; spindle speed: 600 rpm; programmed feed: 0.1 mm/rev, $\lambda = 20$, $\eta = 1$; reference force: 100 N; allowed tracking error: 10 N.)

The conventional adaptive control scheme has been also applied to the turning processes with the same cutting conditions as in the first experiment except for the cutting tool tips. Figure 12 shows the experimental results. At the point where the cutting depth increases, the feedrate decreases abruptly in order to maintain the cutting force at the reference value. Compared to the slide mode controller shown in Fig. 11, it can be identified that the problems in the case of the conventional adaptive controller are that the system response overshoots and undershoots and that the output trajectory fluctuates. Therefore, the experimental results verify the inadequacy of the conventional adaptive control theory in the presence of a nonlinear element due to the four-bit feedrate override command element.

As a second experiment, a different work-piece material of A6066 aluminum is used to verify

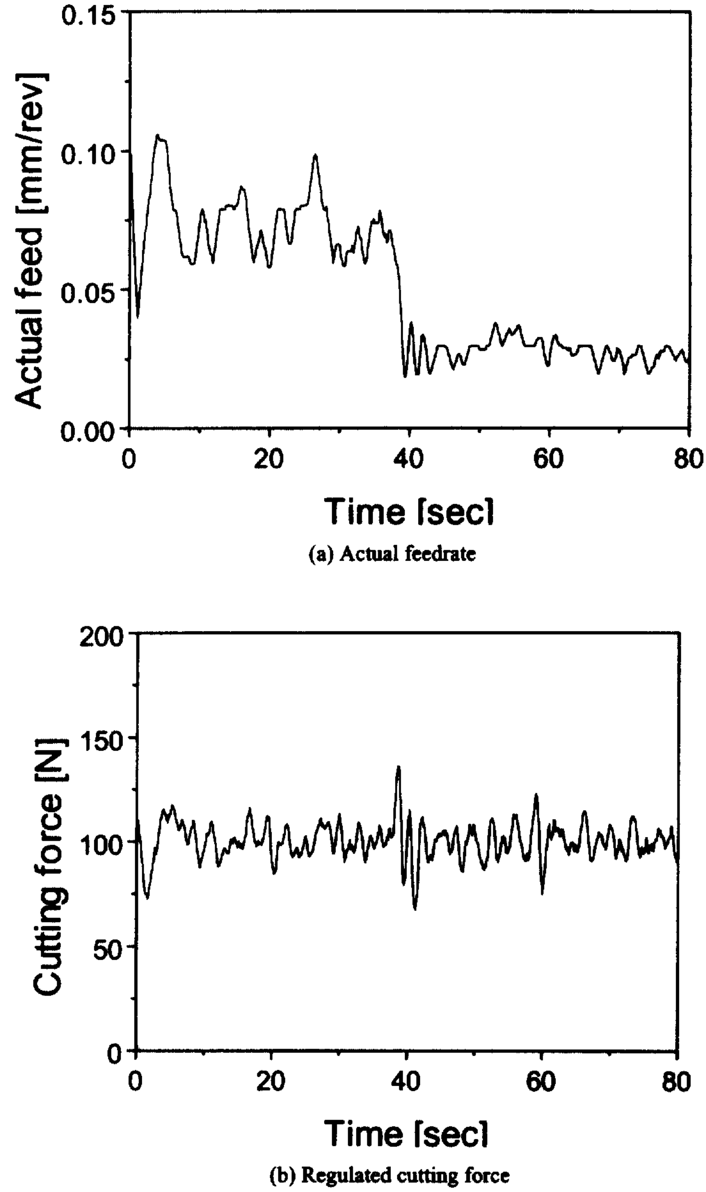


Fig. 12. Conventional adaptive control system response by using the four-bit feedrate override element. (Material: 1024 steel; depth of cut: from 1.0 to 2.0 mm; spindle speed: 600 rpm; programmed feed: 0.1 mm/rev; reference force: 100 N.)

the performance of the sliding mode controller subject to the material change. The machining conditions are identical to that of the previous experiment with the exception of work-piece material, and the same sliding surface parameters have been used. However, since aluminum is relatively low in strength compared to steel, the reference force is selected at 50 N with 5 N of tracking error allowed. The average error is 4.4 N, which is in agreement with the desired range.

The experimental results are shown in Fig. 13. The second experimental work proves that the cutting force tracks the desired value with a guaranteed precision in the face of a change in material, not to mention a change in depth of cut.

For the third experiment, the same sliding mode control is applied to a different type of machining process. The depth of cut is programmed to undergo a continuous change instead of a step change. The machining process can be considered a reverse of tapering. In other words, the depth of cut increases from 1 to 2 mm at a constant rate. The work-piece material is 1024 steel and the machining condition and sliding surface parameters are identical to those of the first experiment. The reference forces and tracking precision are also chosen to be the same as the first experiment.

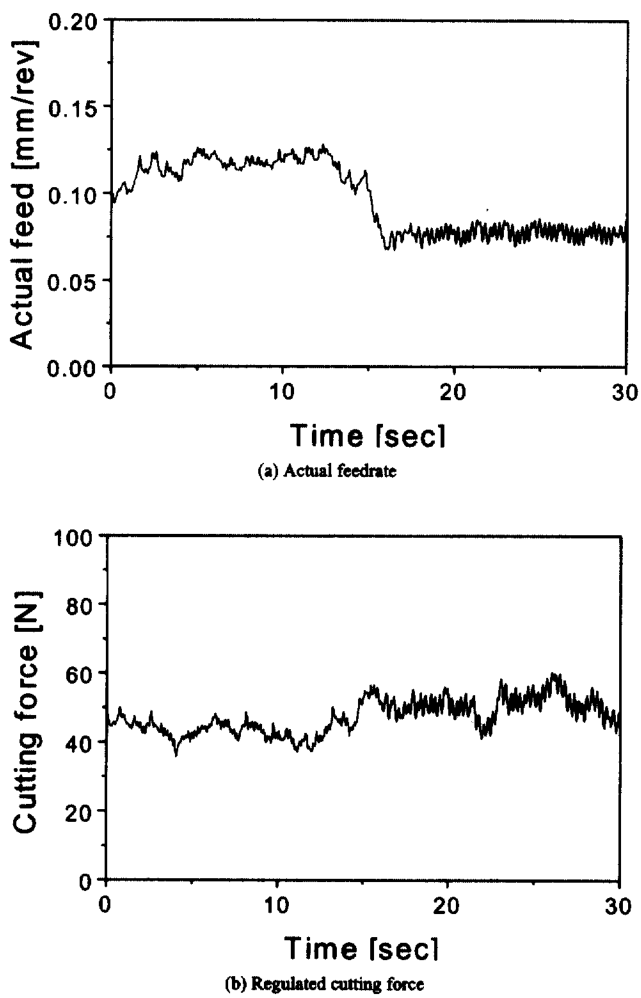
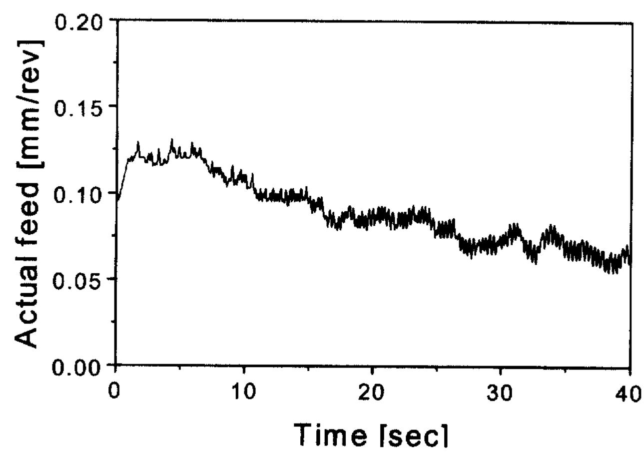


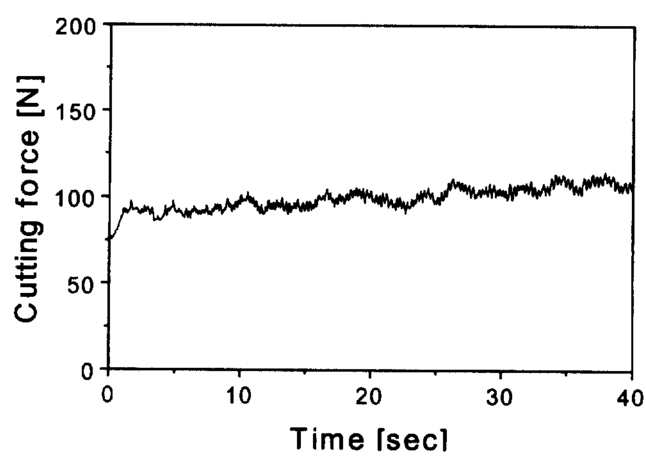
Fig. 13. Sliding mode control system response by using the four-bit feedrate override element. (Work-piece material: A6066 aluminum; depth of cut: from 1.0 to 2.0 mm; spindle speed: 600 rpm; programmed feed: 0.1 mm/rev, $\lambda = 20$, $\eta = 1$; reference force: 50 N; allowed tracking error: 5 N.)

As illustrated in Fig. 14, the average tracking errors are 5.9 N, which do not exceed the allowed errors of 10 N. As the cutting depth increases continuously, the actual feeds decrease accordingly, maintaining the cutting forces at the reference values.

It has been demonstrated that sliding mode control has major advantages in reduction in overshoot and vibration. However, it can be observed that the tendency of the cutting force is similar to that of the depth of cut. In other words, as the cutting depth increases, the cutting force also increases. This is a typical problem arising from indirect measurement of cutting force by current sensing. As discussed in the previous section, the quadratic approximation of the relation between the frictional force and the feed does not completely compensate the nonlinearity of friction. A



(a) Actual feedrate



(b) Regulated cutting force

Fig. 14. Sliding mode control system response by using the four-bit feedrate override element. (Work-piece material: 1024 steel; depth of cut: from 1.0 to 2.0 mm tapering; spindle speed: 600 rpm; programmed feed: 0.1 mm/rev, $\lambda = 20$, $\eta = 1$; reference force: 100 N; allowed tracking error: 10 N.)

more precise model of the frictional force in relation to the feedrate can solve this problem, which is left for future work at this point.

5. Conclusions

The work discussed in the previous chapters can be summarized as follows:

1. Due to the nonlinear four-bit feedrate command element in commercialized CNC, the general adaptive control scheme for the cutting force regulation has shown that the cutting force fluctuates considerably and that the overshoots are large. For this motivation, a slide mode controller has been suggested in this paper.
2. The slide mode control scheme has been developed based on the simplified models of the turning process and the CNC servo system. In order to account for the presence of modeling imprecision and of disturbances, the thin boundary layer has been assigned to the ideal sliding surface. This boundary layer is the trade-off between tracking error and robustness to unmodeled dynamics.
3. The suggested slide mode control scheme for cutting force regulation in turning processes has been modeled, and its effects on cutting force control have been studied through simulation study. It has shown that the suggested scheme makes the system insensitive to nonlinearity which has been resulted in by the presence of the four-bit discrete feedrate override command element in the commercial CNC lathe.
4. The continuous sliding mode controller has been applied to a commercial CNC lathe system, and its performance has been verified through a series of experimental works. In the experiments, the continuous sliding mode control has been proven to be effective in overshoot and vibration reduction in turning operations subject to both the work-piece materials and the stepwise or continuous changes in cutting depth. It has been verified by the experimental works that the performance of the suggested slide mode controller is far better than the conventional adaptive controller in the aspects of cutting force fluctuation.
5. As a practical means of applying the sliding mode control algorithm, the cutting force has been measured indirectly by sensing the servo-motor current, and a command feedrate transmission system with standard interface between the sliding mode control system and the CNC of a conventional CNC lathe has been devised.

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