Proceedings of the 11th
KACC, October 1996

Adaptive cutting force controller for milling processes by using AC servodrive current measurements

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Abstract This paper presents an adaptive cutting force controller for milling process, which can be attached to most commercial CNC machining centers in a practical way. The cutting forces of *X*, *Y* and *Z* axes are measured indirectly from the use of currents drawn by AC feed-drive servo motors. A typical model for the feed-drive control system of a horizontal machining center is developed to analyze cutting force measurement from the drive motor. The pulsating milling forces can be measured indirectly within the bandwidth of the current feedback control loop of the feed-drive system. It is shown that indirectly measured cutting force signals can be used in the adaptive controller for cutting force regulation. The robust controller structure is adopted in the whole adaptive control scheme. The conditions under which the whole scheme is globally convergent and stable are presented. The suggested control scheme has been implemented into a commercial machining center, and a series of cutting experiments on end milling and face milling processes are performed. The adaptive controller reveals reliable cutting force regulating capability under various cutting conditions.

Keywords Cutting Force Regulation, Adaptive Control, Milling Process

1. Introduction

Although, the use of Computer Numerical Control (CNC) machining centers has expanded rapidly during the past decades, it still necessitates the demand for qualified programmers and operators. They have to manipulated several cutting conditions such as feedrate and spindle speed by using machining handbooks and their previous experience on machinig.

For this reason, a series of studies on Adaptive Control with Constraints (ACC) of cutting forces has been done in a laboratory environment. The state of the art is well reviewed by Ulsoy and Koren (1993). The basic objective is the on-line manipulation of the cutting conditions (typically feedrates) based on the measurement of actual cutting process characteristics (typically cutting forces). However, as Ulsoy and Koren (1993) have mentioned it, very few adaptive control systems have been accepted by machine tool manufacturers so far since all the aforementioned research works have common practical drawbacks such as impraticality of cutting force sensors.

The objective of the research work reported in this paper is to develop an ACC system which can solve such practical drawbacks based on the following approaches :

(1) As a first point, in this research work, the cutting forces of *X*, *Y* and *Z* axes are measured indirectly from the use of currents drawn by feed-drive AC servo motors.

(2) Secondly, an adaptive robust control scheme for cutting force regulation is suggested, where the controller structure is a general pole assignment PID controller.

Stein et al. (1986) studied on the sensitivity analysis of the current drawn by DC servo drive motors to the cutting forces in turning processes. Altintas (1992) discussed the viability of using armature current of a DC servo motor as a cutting force measurement sensor in milling processes. It has been verified that the pulsating milling forces can be predicted from the current measurement at tooth passing frequencies which are within the bandwidth of the servo. Since the contemporary CNC is adopting the AC servo-drive system, a new indirect cutting force measurement method should be studied on the AC servo-drive system, compared with the previous works on DC servo-drive systems.

The remainder of this paper is organized as follows: In order to analyze the use of current signals from the AC feed-drive system for cutting force measurements, the modeling of the dynamic systems between cutting force signals and AC feed-drive current signals of a CNC machining center are presented in the next section. The subsequent section presents the controller structure which has been developed for robust adaptive cutting force regulation. The experimental results from the application of the suggested scheme to face cutting processes are shown.

2. The indirect cutting force sensing system

A horizontal machining center, with a 32-bit microprocessor FANUC CNC system model 15-M, has been used in this study. The three feed axes (*X*, *Y*, and *Z*) of the machine have ball screw drives and are directly driven by permanent magnet synchronous (that is, PMSM type) AC servo motors. The block diagram of the feed-drive system can be derived as in Fig.1 based upon the technical data provided from FANUC Ltd.(Koga, 1994).

The linear transfer function between the variation of the feedrate command v_c and the variation of the actual feedrate v_a for the *X*-axis feed-drive system is identified as follows with the CNC servo parameter value in Fig.1. There exists an inevitable time delay T of 0.08 seconds at the input channel of the feedrate command when the command signal is processed at the programmable machine controller (PMC) of the CNC system.

$$\frac{v_a(s)}{v_c(s)} = \frac{497000e^{-0.08s}}{(s+14.0)(s^2+155s+35500)} \quad (1)$$

Considering the practical frequency range of 0~10 Hz, the transfer function can be approximated by

$$\frac{v_a(s)}{v_c(s)} = \frac{14.0e^{-0.08s}}{s+14.0} \quad (2)$$

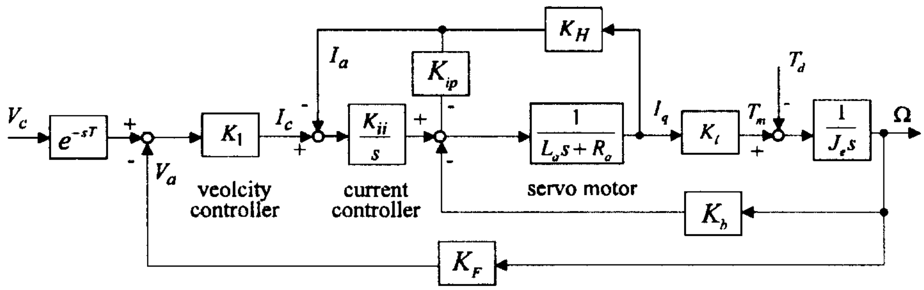
On the other hand, the transfer function of a x-axis feed drive servo system as a remote cutting force sensing system with the cutting force input and feed drive servo motor current output is written as,

$$\frac{K_t i_q(s)}{t_d(s)} = \frac{3570(s+139)}{(s+14.0)(s^2+155s+35500)} \quad (3)$$

where t_d is the variation of the disturbance torque T_d (see Fig.1).
This transfer function can be approximated as follows by neglecting the poles which do not strongly affect the current loop dynamics:

$$\frac{K_t i_q(s)}{t_d(s)} = \frac{255(s+139)}{s^2+155s+35500} \quad (4)$$

The experimental and simulation frequency responses of the current-cutting force sensing system for the *X*-axis feed-drive system are shown in Fig.2 The simulation response is in good agreement with the experimental



V_c	feedrate command $[mm/\min]$	-	V_a	actual feedrate $[mm/\min]$	-
K_1	velocity proportional gain $[V/(mm/\min)]$	0.08	K_F	velocity feedback gain $[(mm/\min)/(rad/\sec)]$	95.493
I_c	current command $[V]$	-	I_a	feedback current $[A]$	-
K_{ii}	current integral gain $[1/\sec]$	6.91	K_{ip}	current proportional gain $[-]$	0.0088
K_H	current feedback gain $[V/A]$	5.93	L_a	armature coil inductance $[mH]$	1.20
R_a	armature coil resistance $[ohms]$	0.15	I_q	actual current $[A]$	-
K_t	torque constant $[kgf\cdot m/A]$	0.165	K_b	back EMF constant $[V/(rad/\sec)]$	0.38
T_m	motor drive torque $[kgf\cdot m]$	-	T_d	disturbance torque $[kgf\cdot m]$	-
J_e	equivalent feed-drive inertia $[kgf\cdot m\cdot \sec^2]$	0.0146	Ω	angular velocity of motor shaft $[rad/\sec]$	-

Fig.1 Block diagram of the FANUC feed-drive system

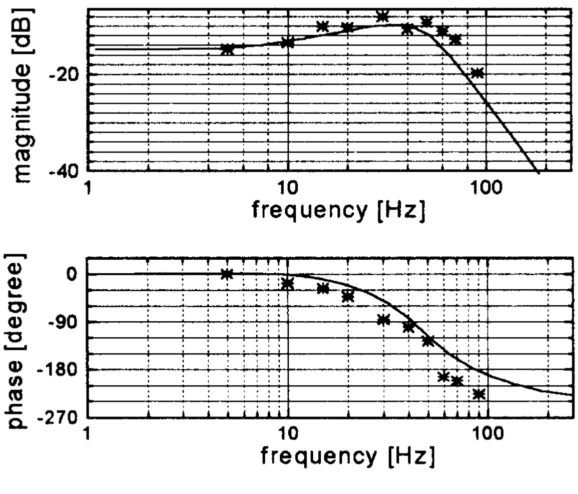


Fig. 2. Frequency response of the feed drive system $K_t i_q(s)$ / $\tau_d(s)$

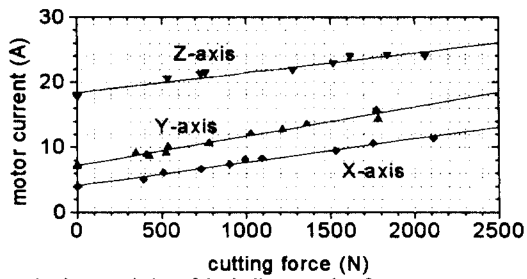


Fig.3 Static characteristics of the indirect cutting force measurement system

result within the bandwidth of the system. The frequency response in Fig.2 indicates that the current sensor bandwidth is approximately 62 Hz, and the cutting forces may be tracked by the current when tooth passing frequencies are below this frequency.

In the model shown in Fig.1, the motor drive torque T_m is exerted in accelerating the equivalent feed-drive inertia J_e, and in overcoming the disturbance torque T_d. The disturbance torque T_d consists of the friction torque in the drive T_f and the cutting torque T_c reflected on the motor shaft.

$$T_m = J_e \frac{d\Omega}{dt} + T_d \tag{5}$$

where

$$T_d = \mathbf{sgn}(\Omega)T_f + T_c \tag{6}$$

On the other hand, the motor drive torque T_m is proportional to the q-axis equivalent current in the case of PMSM type AC servo motors as follows:

$$T_m = K_t I_q \tag{7}$$

where, K_t is a torque constant, I_q is the q-axis equivalent stator currents, respectively.

From equation (5) and (7), assuming steady-state feedrates yields

$$K_t I_q \cong T_d = \mathbf{sgn}(\Omega)T_f + K_f F_c \tag{8}$$

where K_f is the cutting force transmission gain as a torque. A series of experimental cutting results in the following linear relationships from the least square regression of the recorded data of cutting forces F_c and equivalent currents I_q (see Fig.3),

X-axis: $I_{qx} = 4.12 + 0.00362F_{cx}$ (9)

Y-axis: $I_{qy} = 7.24 + 0.00450F_{cy}$ (10)

Z-axis: $I_{qz} = 18.5 + 0.00289F_{cz}$ (11)

Equations (9), (10) and (11) describe the static characteristics of the indirect cutting force measurement system.

3. Robust adaptive cutting force regulation scheme

An adaptive robust control scheme, combining on-line cutting process estimation and control, has been suggested by the authors (Kim *et al.*, 1994). The basic structure of the proposed adaptive controller consists of (1) a controlled plant model, (2) a model parameter estimator, (3) a robust servocontroller, and (4) a controller adjustment mechanism.

The controlled plant consists of a CNC feed-drive servomechanism S and a cutting process P as shown in Fig.4. The control objective is to generate a series of feedrate command signals V_C which regulate the cutting force F_c so that its peak outputs maintain a constant allowable value regardless of the variation of depth-of-cut D and/or workpiece material M.

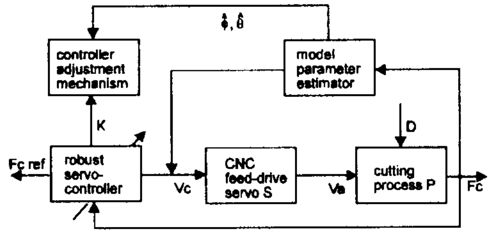


Fig.4 Basic structure of an adaptive robust servo control for cutting force regulation

The following discrete-time ARMA model is assumed for the controlled plant:

$$f_c(t)+\phi_1 f_c(t-1)+\phi_2 f_c(t-2)=\theta_0 v_c(t-1)+\theta_1 v_c(t-2) \qquad (12)$$

where $f_c(t)$ and $v_c(t)$ are the sampled data series.

The controlled plant model (11) can written as:

$$\begin{cases} x(t+1)=\Phi x(t)+\Gamma v_c(t) \\ f_c(t) \;=C_m\, x(t) \end{cases} \qquad (13)$$

where

$$x(t)\equiv[x_1(t),x_2(t)]'$$

$$\Phi\equiv\begin{bmatrix}0 & -\phi_2\\ 1 & -\phi_1\end{bmatrix};\ \Gamma\equiv\begin{bmatrix}\theta_1\\ \theta_0\end{bmatrix} \qquad (14)$$

$$C_m\equiv\begin{bmatrix}0 & 1\end{bmatrix}$$

Model (12) can be written in the following form :

$$f_c(t)=\Phi_m(t-1)^T\theta_p \qquad (15)$$

The model parameter vector θ_p is then estimated by using the on-line least squares method with covariance resetting and dead-zone control (Goodwin and Sin, 1984).

For the purpose of improving the robustness of the adaptive control scheme, achieving the explicit closed-pole assignment, and easily extending the whole scheme to multi-input multi-output cases, a robust servocontroller structure is adopted, which consists of a servo-compensator, a stabilizing compensator, and a feedback controller (Davison *et al.*, 1981).

The servo-compensator is constructed in such a way that its dynamic modes should be identical with those of command inputs and/or disturbances. This is a generalization of the integral controller of the classical control theory. Since the command input is a constant allowable cutting force in this research work, the servo-compensator can be presented as follows:

$$\eta(t+1)=\eta(t)+Te(t);\ \ e(t)=f_c(t)-f_c^{*}(t) \qquad (16)$$

where T is the sampling time [sec] and f_c^{*} is the cutting force command input [N].

The stabilizing compensator stabilizes the augmented system which can be obtained by applying a servo-compensator (16) to the controlled plant (13). A stabilizing compensator has been chosen:

$$\varepsilon(t+1)=\gamma_0\varepsilon(t)+\gamma_1 f_c(t)+\gamma_2\eta(t) \qquad (17)$$

Applying the feedback controller

$$v_c(t)=k\eta(t)+\gamma_3 f_c(t)+\gamma_4\varepsilon(t) \qquad (18)$$

to the controlled plant (13) with the servo-compensator (16) and the stabilizing compensator (17) yields the following closed-loop system:

$$X(t+1)=\Phi(K)X(t)+\Gamma(K)f_c^{*}(t) \qquad (19)$$

$$f_c(t)\;=C(K)X(t) \qquad (20)$$

where

$$X(t)\;\equiv[x(t),\eta(t),\varepsilon(t)]'\in R^M \qquad (21)$$

$$\Phi(K)\equiv\begin{bmatrix}\Phi+\Gamma\gamma_3 C_m & \Gamma k & \Gamma\gamma_4\\ B_d^{*}C_m & C_d^{*} & 0\\ \gamma_1 C_m & \gamma_2 & \gamma_0\end{bmatrix} \qquad (22)$$

$$\Gamma(K)\equiv\begin{bmatrix}0\\ -B_d^{*}\\ 0\end{bmatrix};\ C(K)=\begin{bmatrix}C_m & 0 & 0\end{bmatrix}^T \qquad (23)$$

with $M=4$ and K denoting the controller gain vector:

$$K\equiv[k,\gamma_0,\gamma_1,\gamma_2,\gamma_3,\gamma_4] \qquad (24)$$

The closed-loop system (19) has following properties: There always exists K which can achieve zero tracking or regulation error with an arbitrary damping factor and this controller is robust if and only if

(1) the perturbations of the controlled plant model parameters do not make Φ unstable, and Φ is always asymptotically stable,

(2) (Φ,Γ) is controllable and (C_m,Φ) is observable,

(3) the number of measured outputs is greater than or equal to that of regulated outputs,

(4) the transmission zeroes of (C_m,Φ,Γ) do not coincide with the dynamic modes of the command inputs and disturbances, and

(5) the regulated output is physically measurable.

The controller gain vector K should be adjusted on-line so that the eigenvalues of $\Phi(K)$ of the closed loop system are assigned to the values which can produce a desired damping factor as well as asymptotic stability. In this research work, a parametric eigenstructure assignment approach by output feedback control (Fahmy and O'Reilly, 1988) has been used for the desired closed-loop pole placement.

4. Experimental studies

The schematic diagram of the entire experimental set-up is shown in Fig.5. The base machine tool is a horizontal three axis machining center. The current signals are collected at 500 Hz sampling frequency. The sampling frequency of the adaptive control algorithm is synchronized with the spindle spinning speed. It generates a new feedrate command input on each spin of the spindle.

The feedrate commands are transferred in a practical way to the CNC unit. The adaptive controller generates feedrate override signals ranging from zero to 255% of the programmed feedrate and converts them into 8-bit binary signals which transmitted to PMC unit of the CNC system.

The experiment work has been performed to show how the suggested ACC system works. The material of the workpiece on the right side is 1054 steel, and on the left side is aluminum alloy. The test cut starts from the right side to the left in the X-axis direction of the horizontal machining center. The spindle spinning speed is 400 rpm, and the tool is a three-inserts face-milling cutter with a diameter of 100 mm. The tooth passing frequency is 20 Hz. The radial depth-of-cut is 80 mm and the axial depth-of-cut is varied as shown in Fig.6. The cutting force to be regulated is set to be 500 N in this case.

The control algorithm estimates a new set of model parameters and generates a new feedrate command input at each sampling interval.

The results of real time cutting experiments are shown in Fig.7. The controlled cutting force is the maximum amplitude per spindle revolution. The error bound of the controlled cutting force is within 50 N at the steady state region for the desired command input of 500 N regardless of the change of depth-of-cut and workpiece material (see Fig.7). An overshoot occurs at every step change of depth-of-cut or workpiece materials. This is inevitable because the ACC system needs a certain amount of adaptation time to reach a new state.

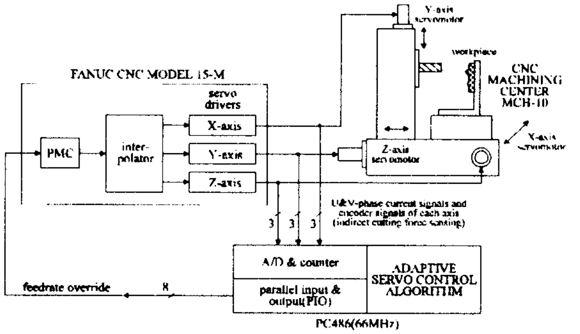


Fig.5 Schematic diagram of the experimental setup

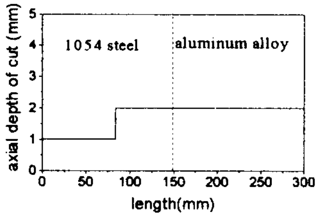
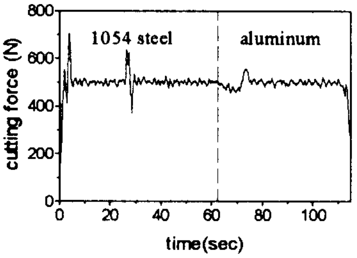
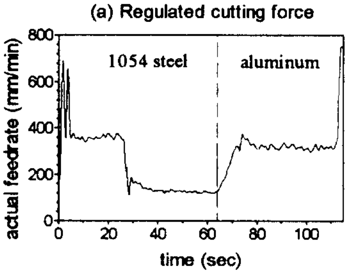


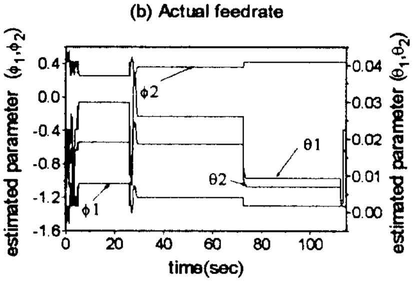
Fig.6 Axial depth-of-cut variation



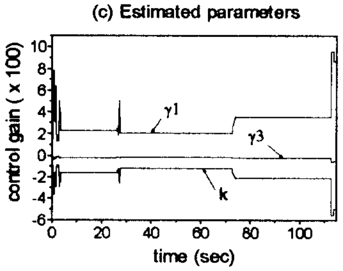
(a) Regulated cutting force



(b) Actual feedrate



(c) Estimated parameters



(d) Updated control gains

Fig.7 Results of the real cutting experiment on the face cutting (spindle speed 400rpm, 3-tooth face cutter with dia. 100mm, radial depth-of-cut 80mm)

Figure 7.c shows that the model parameter estimates of the cutting process converge to a different set of steady state constant values. The control gains are then updated for the new set of model parameters as shown in Fig.7.d.

5. Conclusion

A research work on an indirect measurement of cutting forces for commercial machining centers with AC servo drive system, and its application to the adaptive control of the cutting force has been presented. In summary, the following conclusions can be drawn from this work :

(1) An indirect cutting force measuring system by using AC servo drive current sensing is developed without using a tool dynamometer. The static accuracy is within 8 percent, and the bandwidth is approximately 62 Hz.

(2) An adaptive robust control scheme for cutting force regulation is suggested, where the controller structure is of a general pole assignment PID type. Arbitrary explicit pole assignment is possible.

(3) The real time cutting experiment on face cutting and end-milling processes reveals a good regulating performance of the suggested adaptive control scheme.

(4) Since the experimental set-up is implemented based on a commercial machining center through a standard interfacing method, the developed algorithm can be easily embedded into other machines as an optional equipment.

Acknowledgment

This work has been supported partly by the Engineering Research Center for Advanced Control and Instrumentation (ERC-ACI) at Seoul National University in Korea. The authors gratefully acknowledge the support.

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