Robust Control of Adaptive Cutting for High Efficiency Machinery

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Abstract – This paper is to utilize the quantitative feedback theory to design the robust controller for adaptive feedrate control. The algorithm can dynamically change the adaptive feedrate so that the cutting efficiency can be improved even under different cutting condition. To improve the system robustness, the quantitative feedback theory is utilized to design the robust controller. Simulation and experiments are conducted to provide some evidence on adaptive cutting control.

Keywords – QFT, Robust, Adaptive feedrate control

I. INTRODUCTION

The machine tool usually provide the fixed feedrate during the machining process without consideration of the path trajectory and loading conditions. As the cutting depth increases, the same feedrate can cause the spindle overloaded which might damage the tool and deteriorate the tool life. While the cutting depth decreases, the spindle might only use part of the power and it is not efficiency for the cutting process. Research has been conducted in the past year to provide some approaches on adaptive control of the end milling process. To achieve the adaptive cutting control, the cutting force during machining was evaluated in [1-2]. Then the adaptive feedrate control was proposed by Altintas [3-4] where the adaptive cutting algorithm were proposed to overcome the dynamic changes during the cutting process. However, the parameter convergence rate for the adaptive strategy might cause the long transient performance. Another approach was to utilize the fuzzy control method for adaptive force control [5]. The knowledge based algorithm is not hard to develop, but the algorithm is strongly dependent upon the cutting process. Another approaches including the Genetic algorithm and combining online measurement were proposed in the past [6-7].

Although the literature shows the feasibility of the adaptive cutting method, the real cutting could be more complicated and the controller should be robust to overcome different cutting conditions. In this paper, the robust quantitative feedback theory (QFT) is proposed to overcome the various cutting condition. The system identification of the cutting process is first performed and the various cutting conditions have been considered by setting different dynamic parameters. Furthermore, the effects of measurement delay are considered in designing the QFT controller. Finally, the experiments are conducted to verify the concepts.

II. DEVELOPMENT OF THEORETICAL MODEL

The system dynamics as shown in Fig. 1 is shown in Fig. 1 which includes the controller, servo dynamics, and cutting process. In the following the models for the servo control and cutting process are derived.

A. The Model of Servo Feed System

The dynamic model of the servo system can be represented by a model for the velocity loop. Because the bandwidth of the current loop is much higher than the velocity loop, the transfer function of the velocity loop can be represented as a second order system given as the following where K_p, ω_n, η are the gain, natural frequency, and damping ratio, respectively [8-10].

$$G_s(s) = \frac{K_p}{s^2 + 2\eta\omega_n s + {\omega_n}^2} \tag{1}$$

where K_p, ω_n, η is the gain, natural frequency and dmaping ratio. After discretization of Eq. (1), the discrete time model in z domain can be represented as.

$$\frac{K_p(Fz+G)}{{\omega_n}^2(z^2 - 2exp(\xi\omega_n T)cos(\omega T)z + exp(-2\xi\omega_n T)} \tag{2}$$

where

$$F = \left(1 - exp(-\xi\omega_n T)cos(\omega T) - \xi\big/\sqrt{1-\xi^2}\, exp(-\xi\omega_n T)sin(\omega T)\right)$$

$$G = \left[exp(-\xi\omega_n T)\left(exp(-\xi\omega_n T) - cos(\omega T) + \xi\big/\sqrt{1-\xi^2}\, sin(\omega T)\right)\right]$$

$$\omega = \omega_n\sqrt{1-\xi^2}$$

B. Model of the Cutting Process

From the research in [2-3], the cutting process can be described by the following dynamic equations.

$$\Delta_x(i) = \frac{F_c(i)}{K_t} \tag{3}$$

where K_t is the end mill's stiffness and

$$F_c = K_s abh_c(i) \tag{4}$$

Here K_s is the cutting constant, a is the axial depth, b is the radial immersion ratio, $h_c(i)$ is the chip load under each sampling rate.

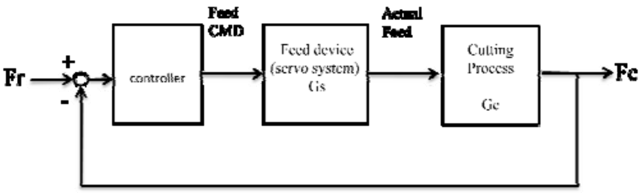

Fig1. Block Diagram of Adaptive Cutting Process

After substituting Eq. (3) into Eq. (4), the cutting forces versus feedrate can be represented as:

$$\frac{F_c}{v} = G_c(z) = \frac{\beta z^{-1}}{1+\alpha z^{-1}} \tag{5}$$

where $\mu = \frac{K_s ab}{k_t}, \alpha = -\frac{\mu}{1+\mu}, \beta = \frac{k_t}{Mn} \cdot \frac{\mu}{1+\mu}$, M is the flute, and n is the spindle speed(rev/sec)

III. EXPERIMENTS ON SYSTEM IDENTIFICATION

In order to validate the derived model, experiments are conducted and the system parameters are identified. To provide the data for the robust control, different cutting conditions were conducted. The FANUC controller is used for the target controller and the data were obtained using the FOCAS functions. The cutting forces were measured by using the dynamometer. The overall experimental setups are shown in Figs. 2 and 3. The cutting conditions are listed in Table 1.

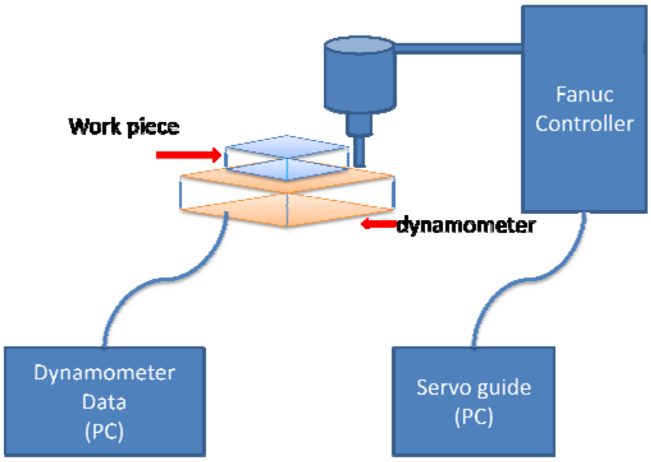

Fig. 2 Experimental setup

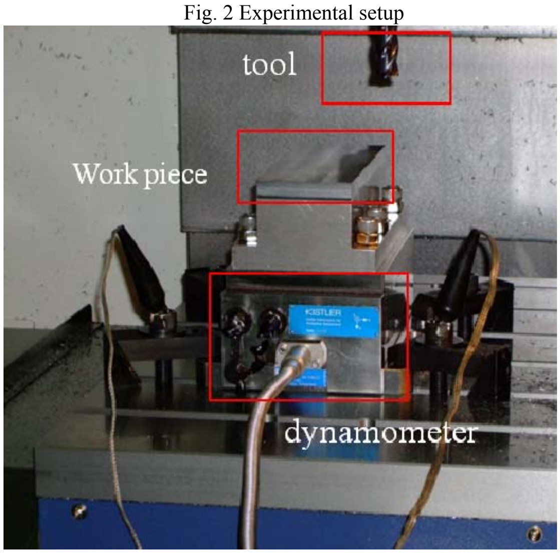

Fig. 3. Picture for Adaptive Cutting System Identification Process

The data were analyzed and process. The model is developed using autoregressive with exogenous input (ARX) model. The raw data and experimental data under the ARX shown in Fig. 4 which validate the model accuracy. As shown in Table 1, different feedrates are selected and identification process is repeated to ensure that Eq. (5) can be used to represent to cutting process.

Table 2 shows the identification results where the parameters in Eq. (5) can be found to vary in a wide range. The DC gain and bandwidth varies from 0.6 to 48 and 11 to 300 rad/sec, respectively. Because the dynamics of the cutting process varies dramatically, the robustness of the controller design must be considered carefully in order to provide a stable adaptive cutting control.

Table I
EXPERIMENTS UNDER DIFFERENT CUTTING CONDITIONS

Work piece：S45C ,200x75x80mm；Tool：4-flute end mill ,diameter 20mm				
Depth of cut(mm)	10,8,6,4,2	2	2	2
Width of cut(mm)	2	10,8,6,4,2	2	2
Spindle speed(rpm)	3000	3000	3000,27002400,2100,2100	3000
Feed per tooth(mm/min)	0.08	0.08	0.08	0.1,0.09,0.08,0.07,0.06

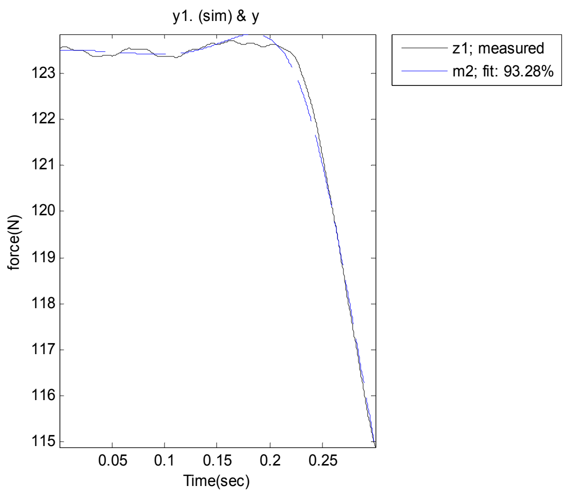

Fig. 4 Validation of the ARX model

Table 2 System Parameters

	Minimum	maximum
α	0.7	0.99
β	0.2	0.48
Bandwith (rad/s)	11	300
Dc gain	0.6	48

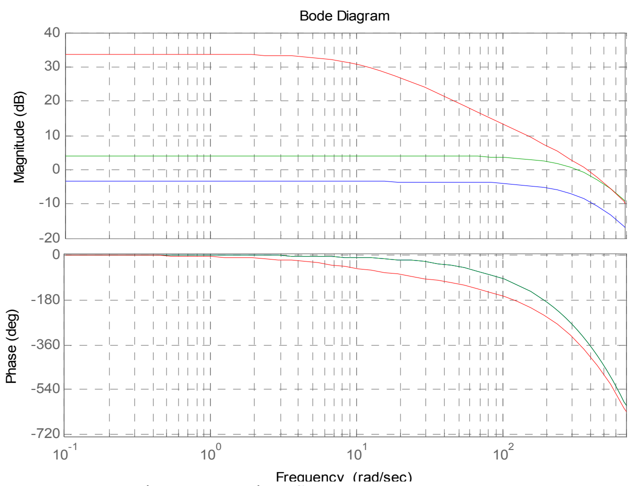

Fig. 5 Uncertainty Spectrum

IV. CONTROLLER DESIGN AND SIMULATION RESULTS

To achieve the robustness, the quantitative feedback theory (QFT) is applied to design a controller such that the system variation is considered explicitly. With the QFT controller, one can design a robust controller to consider the large system uncertainties as shown in Fig. 5.

The QFT controller starts by setting a plant template in the Nichols chart and then specify the robust stability using the gain and phase margin. The loop gain (denoted as L(jω)) must not enter the U-contour in the Nichols chart at any of the given frequencies [11]. The designed control is shown in Fig. 6. According to the designed controller, simulation is conducted to ensure that the QFT can perform well even under different cutting condition. The step response under DC gains shown in Table 2 are shown in Figs. 7 and 8. It is clear that the QFF controller can provide a stable and rapid responses for different cutting process.

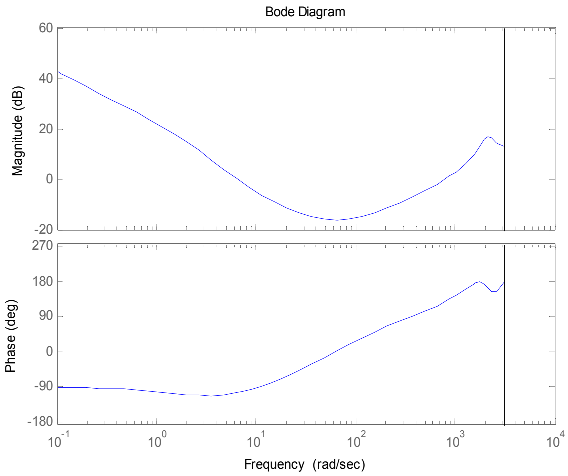

Fig. 6 Controller Spectrum

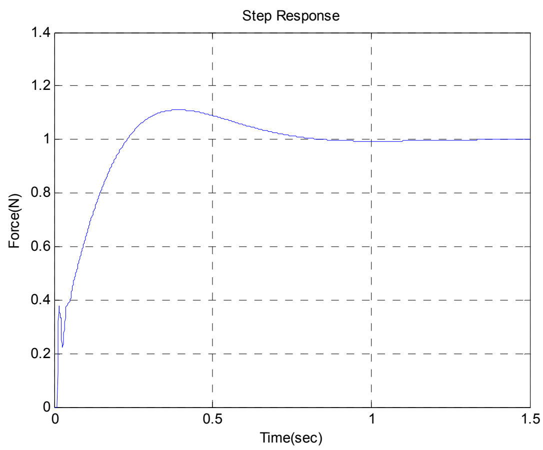

Fig. 7 The step resposne under minimum gain

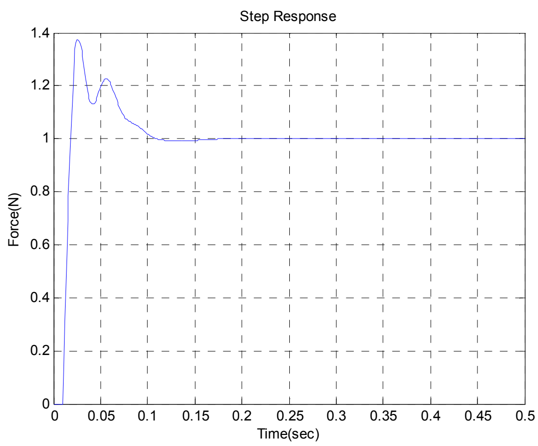

Fig. 8 The step resposne under maximum gain

V. CONCLUSION

The experiments were conducted to meausre the system paramters of the cutting process and the QFT controller is proposed to overcome the large uncertainties due to the varying cutting condition. From the simulation results, one can find that the system is stable and the repsonse can reach the steady state (less than 1 second) even under different cutting condition.

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