Adaptive Cutting Force Control for CNC Milling Machine

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Abstract.

This paper presents the adaptive cutting force control for CNC milling machines. The research scheme divided the mathematical models, consisted of two parts: model of the feed drive system. Then it’s designed to the adaptive cutting force controller using Lyapunov’s method. The dynamometer is used to sense the cutting force and feedback to the cutting force controller. The output signal of the controller is a feed rate volume of CNC controller to control the feed drive system during a milling process. For experimental, it's defined 3 different depths of cut(DOCs). The experimental results compared to that between the actual cutting force response and the target cutting force. As experiment result, it can control the cutting force smoothly, the tool life increased and acceptable practice.

Keywords. Adaptive control, Cutting force, CNC milling machine; Feed drive system, Mathematical Models.

1. INTRODUCTION

The utilization of CNC milling machine has expanded rapidly in THAILAND, such as a metal forming industry and metal machining needs to increase efficiency and reduce production costs. The advantage of CNC milling machine is optimization of the production process, and a not very skilled CNC operator features. However, the disadvantages of conventional milling operation are the calculation of parameters of CNC milling machines, such as the spindle speed and feed rate in order to identify the cutting force appropriated for the DOC and the hardness of work piece. The most parameters are defined by CAD/CAM programmer which calculated from a manual of end mill tools. Thus, the utilization of many CNC milling machine is ineffective. The condition of operating the CNC milling machines require that parameters must be configured very carefully in order to avoid any damages and/or failure. Consequently, many CNC milling machines cannot work effectively and work under the milling process conditions that are not the optimal criteria. Cutting force [1-5] is one of the important parameters of CNC milling machines. It is very useful the quality inspection of End mill tool and work piece. Moreover, the suitable cutting force prevents tool breakages, improves the surface quality of work piece, and enables further development of cutting-force CNC controllers. Therefore, the use of CNC milling machines will rely on the expertise of the CNC milling machine. To address the issues, [6-9] proposed the adaptive cutting force control system. The authors however ignored the parameter of the feed drive system used in the analysis, giving rise to design the cutting force control.

According such the problems, this research presents the cutting force control for CNC milling machines, which online adjusted the CNC parameters while CNC milling machine runs on. The control system is designed to adaptive cutting force sliding mode control to optimize the milling process, reduce the tool wear, reduce the tool breakage [1-3], and increase the tool life [1]. The controller performs to control the cutting speed [1,2] by adjusting the feed rate volume in real time [6]. For control system design, it's divided the mathematical models consisted of two parts: Model of the feed drive system, in which the friction force was integrated into the model and Model of the milling process. Then, the controller is designed to be the adaptive sliding mode cutting force control. The target cutting force considers based on the hardness of steel, feed rate, cutting speed, and spindle speed, which is determined by CNC operator. The cutting force errors were then computed and were inputs of a Lyapunov's algorithm-based adaptive mechanism [10,11] for the output tracking error convergence and the cutting force [5,6]. The experimental results indicated that the proposed integrated technique could reasonably control the cutting force and subsequently the cutting force, thus a good candidate for use in CNC milling machines.

2. MATHEMATICAL MODELS OF THE CUTTING PROCESS

The CNC milling machine consists of the feed drive system for 3 set (X-Y-Z Axes) and spindle system, as shown in Figure 1

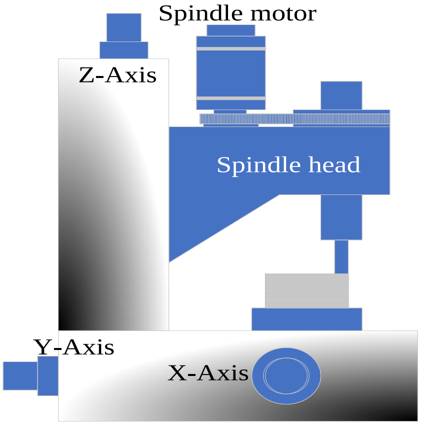


Figure 1 CNC Milling Machine

The principle of the CNC milling machine is that the work piece must be installed on atop the machine tool table. The machine operator will enter the part program to the CNC Controller, press the cycle start button for the CNC milling machine activated. After that, each axis of the feed drive system moves according to the part program.

2.1. Feed Drive System

Generally, the feed drive system of CNC milling machines have the basic components as follows: servo motor driver, servo motor, ball screw, ball nut, coupling, slide way, thrust bearings, saddle, machine tool table, end mill tool, and lubrication system as shown in Figure 2. The work piece will move horizontally along X-axis and Y-axis while end mill tool moves vertically along Z-axis. For the milling process, the dynamometer must be installed on machine tool table to sense the cutting force to the cutting force controller

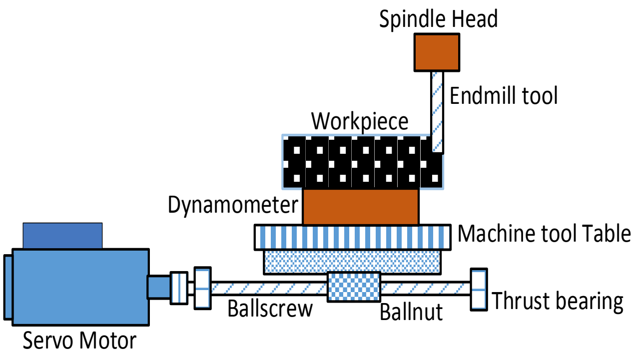


Figure 2 the feed drive system

The basic of CNC milling machine is that the work piece is mounted on a machine tool table, and moving toward the end mill tool, called milling process. The block diagram of the milling process is written, as shown in Figure 3. It can be defined by using the mathematical model of the milling process into second order equation [7]. From the analysis, the mathematical model of the process consisted of 2 parts: the model of feed drive system and model of milling process as shown in Figure 3

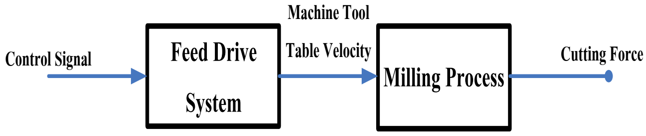


Figure 3 Block diagram of the milling process

2.2. Model of feed drive system

A mathematical model of feed drive system, it consists of servo motor driver, servo motor, ball screw, ball nut, coupling, slide way, thrust bearings, saddle, and machine tool table as shown in Figure 4. It can be modeled mathematically by the first order equation of 1.

$$f_r = ms\dot{x} + d\dot{x} \tag{2.1}$$

where

m : the moment of inertia.

d : the damping coefficient.

x : the machine tool table position

$\dot{x}$: the machine tool table velocity

$\ddot{x}$: the machine tool table accelerate

f_r : the control signals.

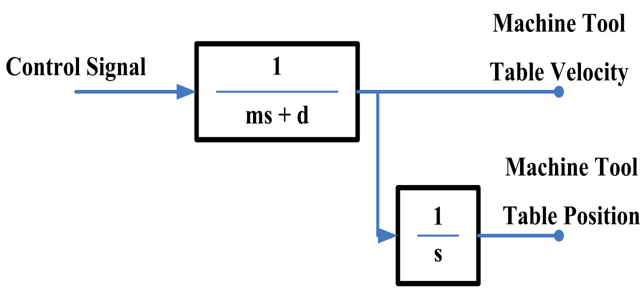


Figure 4 Block diagrams of the feed drive system

2.3. Model of the milling process

A model of the milling process is the work piece which mounted on a machine tool table, and moving toward the end mill tool as shown block diagram in Figure 5. Consequently, the milling process can be defined by mathematical modeling the first order equation in 2.

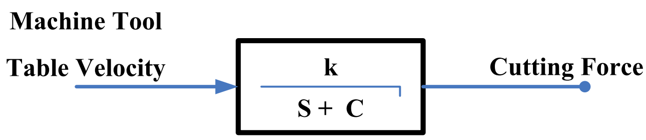


Figure 5 Block diagrams of the milling process.

$$k.v = \dot{F}_c + cF_c \tag{2.2}$$

where

F_c : cutting force.

v : the machine tool table velocity

k : the milling process gain

c : the coefficient of cutting force, based on cutting depth and spindle speed.

Equation (1) and (2) can be written as the transfer function of the milling process, shown in equation (3).

$$kf_r = m\ddot{F}_c + (mc + d)\dot{F}_c + dcF_c \tag{2.3}$$

Then, the equation (3) enter into the design process of cutting force controller.

3. CONTROLLER DESIGN

In the design of the adaptive cutting force control, the model of feed drive system and model of milling process were combined into the cutting force process transfer function. The output of the cutting force controller is defined to be the feed rate by adjusting the feed rate volume to the CNC controller, as shown in the figure. 6, which it's designed as adaptive cutting force control, using Lyapunov's function.

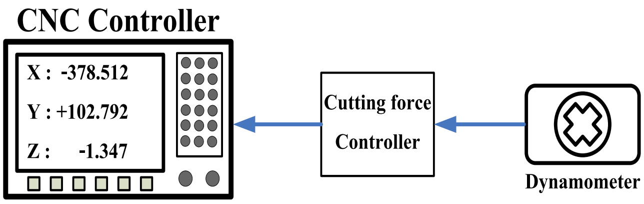


Figure 6 Block diagram of Cutting force controller

From equation (3), the state space equation can be rewritten as equation (4).

$$m\ddot{F}_c + (mc + d)\dot{F}_c + dcF_c = kf_r \tag{4}$$

Defined the signal control as

$$f_r = \hat{m}\ddot{F}_d + \hat{\alpha}\dot{F}_d + \hat{\beta}F_d - KdE \qquad (5)$$

Where

F_d is the target cutting force.

Kd is PD control gain.

α is equal to . $(mc+d)$ and $\tilde{\alpha} = \alpha - \hat{\alpha}$

β is equal to . dc and $\tilde{\beta} = \beta - \hat{\beta}$

defined

$$\tilde{F} = F_c - F_d \text{ , } E = \dot{\tilde{F}} + \lambda\tilde{F}$$

where

$\tilde{F}$ is the error of cutting force.

λ is the sliding mode gain.

Substitute equation (5) into equation (4)

$$m(\ddot{\tilde{F}}_c + \ddot{F}_d) + \alpha(\dot{\tilde{F}}_c + \dot{F}_d) + \beta(\tilde{F}_c + F_d) = k(\hat{m}F_d + \hat{\alpha}F_d + \hat{\beta}F_d - KdE) \qquad (6)$$

Substitute in equation (6), and derived at equation (7).

$$m\ddot{\tilde{F}}_c + \alpha\dot{\tilde{F}}_c + \beta\tilde{F}_c = \tilde{m}\ddot{F}_d + \tilde{\alpha}\dot{F}_d + \tilde{\beta}F_d - KdE \qquad (7)$$

Equation (7) is written a state error, and derived at equation (8)

$$\dot{e} = Ae + Bw\tilde{\phi} \qquad (8)$$

From equation (8) defines the Lyapunov's as

$$V = e^T Pe + \tilde{\varphi}^T \Gamma^{-1}\tilde{\varphi} \qquad (9)$$

The Matrix and are symmetry matrix and positive definite.

Differential equation (9) is as follows

$$\dot{V} = e^T P\dot{e} + \dot{e}^T + 2\tilde{\varphi}^T \Gamma^{-1}\dot{\tilde{\varphi}} \qquad (10)$$

From equation (10), it specified that and resulted in the adaptation law as follows.

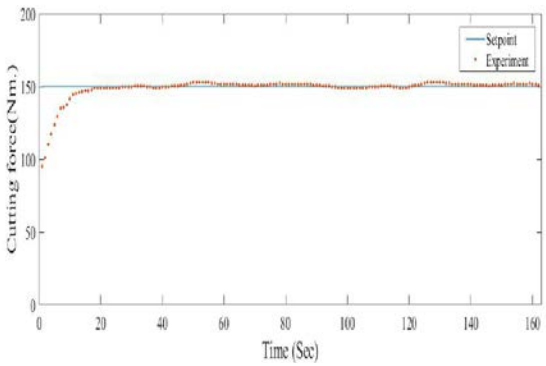
$$\dot{\tilde{m}} = -\gamma_1 \dot{F}_d E$$

$$\dot{\tilde{d}} = -\gamma_2 \dot{F}_d E$$

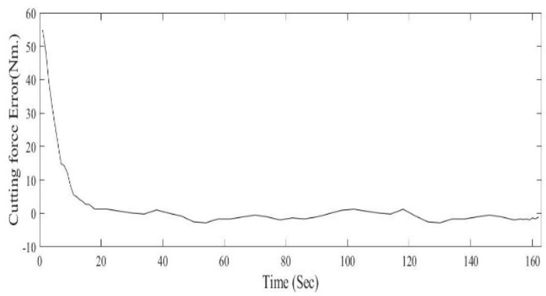
$$\dot{\tilde{c}} = -\gamma_3 \dot{F}_d E$$

4. EXPERIMENT RESULTS

The experiments of the proposed the cutting force controller were carried out using Makino CNC machine with a 10 millimeter diameter Flat End Mill tool, spindle speed of 3000 rpm, IBM personal computer Pentium 450 MHz, which installed the 6 channel digital to analog converter card, the 3 channel analog to digital converter card and the up-down counter. Moreover, a 200x200mm KISTLER dynamometer is mounted on the machine tool table for measurement of the actual cutting force to feedback to the cutting force controller. The work piece was SKD41 steel



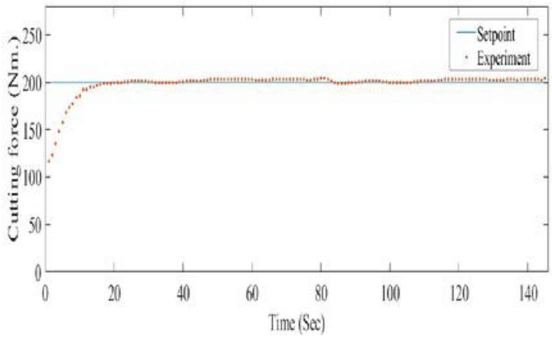
(a)



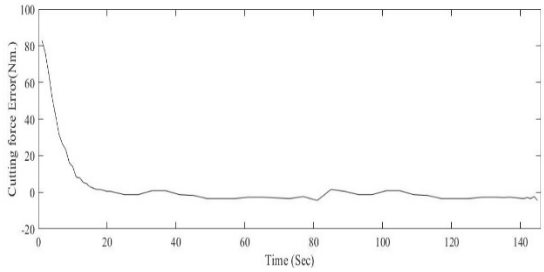
(b)

Figure. 7 Experimental result of milling process at the set point 150 Nm and DOC 1 millimeter. (a) comparison between the actual and the set point. (b) the cutting force error

The experiment results compared to that between the cutting force response and the target cutting force, at 3 different DOCs were 1, 2, and 4 millimeters. The target cutting forces are 150, 200 and 320 Nm, respectively.

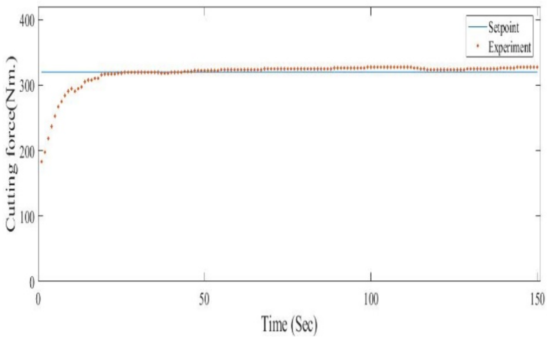


(a)

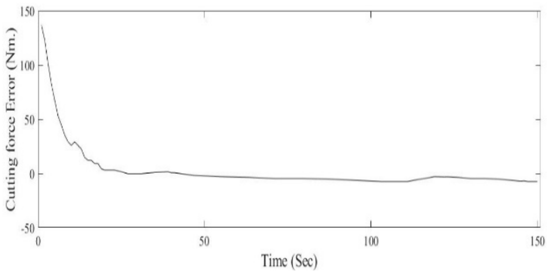


(b)

Figure. 8 Experimental result of milling process at the set point 200 Nm and DOC 2 millimeters. (a) comparison between the actual and the set point. (b) the cutting force error



(a)



(b)

Figure. 9 Experimental result of milling process at the set point 320 Nm and DOC 4 millimeters. (a) comparison between the actual and the set point. (b) the cutting force error

Figure 7 shows the comparison between the actual cutting force and the target cutting force 150 Nm. (DOC 1 millimeter); Figure 8 shows the comparison between the Figure 7 shows the comparison between the actual cutting force and the target cutting force 150 Nm. (DOC 1 millimeter); Figure 8 shows the comparison between the actual cutting force and the target cutting force 200 Nm. (DOC 2 millimeters); and Figure 9 shows the comparison between the actual cutting force and the target cutting force 320 Nm. (DOC 4 millimeters). The results of the controlling show that the cutting force response of 3 levels was converged to the target value and smooth. The cutting force changed based on the feed rate of the feed drive system. As experiment results, it can control the cutting force smoothly and compensate the up milling and down milling of the end mill tool, the tool life increased and acceptable practice.

5. CONCLUSION

This paper presents the adaptive cutting force control for CNC Milling machines. The design of the controller determines the mathematical model of feed drive system to adjust the feed rate while CNC milling machine runs on. As a result of the milling process at 3 different DOCs, actual cutting force response will convergence with the target cutting force, which controls the cutting force smoothly, the tool life increased and acceptable practice.

6. REFERENCES

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