2002년도 대한전자공학회/대한전기학회 시스템 및 제어분야 합동 추계학술대회 논문집(2002.11.30)

Design of Fuzzy Logic Controllers for High-Speed and High-Accuracy CNC machines

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고정밀 고속가공을 위한 CNC머신의 퍼지 제어기 설계

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요 약

이 논문에서는 CNC 머시닝 센터의 두 서보축을 대상으로 가공정밀도를 유지하면서 최고의 이송속도로 가공 속도를 증가시키는 퍼지 제어 기법을 제안한다. 또한 기존의 오차 모델링 방식이 아닌 비선형 궤적에서도 적용이 가능한 최근의 윤곽오차 모델을 사용한다. 퍼지 소속함수의 입력 변수가 허용 오차에 따라 스케일링되고 이송속도와 윤곽오차와의 관계를 퍼지제어 룰에 기초하여 허용 오차안에서 매 시간마다 보다 빠른 이송속도를 찾는다. 모의 실험 결과들이 제안한 방법이 기존의 고정된 이송속도를 사용하는 방법과 유사한 윤곽오차를 보이면서도 빠른 가공을 할 수 있음을 보여준다.

I. Introduction

NC and computer numerical control (CNC) machines have been improved toward high-speed and high-accuracy machining. In biaxial contour motion systems, not only contouring performance but feedrate control is important. However, as contouring speed increases, contour accuracy related to the quality of products may result in poor accuracy. Thus, it is so important to control feedrate adaptively in order to guarantee the required contouring accuracy. And many studies have been conducted to improve contouring accuracy and contouring speed simultaneously within the error bound[2-4].

In this paper, we propose a feedrate control method based on fuzzy rule base. The fuzzy logic controller adjusts feedrate according to the human knowledge base considering the relationship between the contour error and the feedrate. The knowledge representation in fuzzy models employed in this paper is developed by Mamdani[6].

II. The CNC machine system

2.1 Characteristics of CNC machine system

The machining process in the CNC machine system composes moving tools along a trajectory in two or multi dimensional space. In conventional machine tools, the controller for each axis is designed independently without regard to the motion of the other axes shown in Fig. 1.1.

2.2 Contour error model

Generally, the contour error for a curved contour cannot be directly measured and must be computed in every sampling time. Several algorithms for computing the contour error are proposed[1,3,7]. Here, we take advantage of the contour error model[5], which use varying windows. The variable size window is used to find two closest points between previous reference points and the current tool position. With these two points, we can determine the contour error by considering the geometrical relationship.

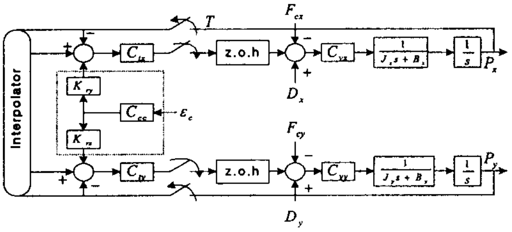

Fig. 1.1 X-Y servo-axes controllers

III. Feedrate control

In this paper, we use the fuzzy logic controller to find a proper feedrate within the tolerable error bound. As illustrated in Fig. 3.1, the fuzzy controller provides adaptive feedrate with interpolator to generate knot points at next sampling time.

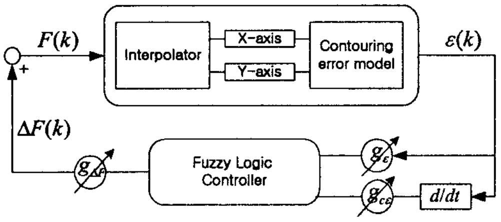

Fig. 3.1 Structure of feedrate control system

3.1 Membership function

In this report, a simple membership function with a bell shape is used to fuzzify the input and output of the fuzzy controller. The bell shape membership function can be defined as

$$\mu_A(x) = e^{\frac{-(x_i - b)^2}{a}}, \quad a > 0 \tag{3.1}$$

3.2 Input and output variables

The two inputs of the fuzzy controller are the contour error, $\varepsilon_c(k)$, and contour error change, $\Delta\varepsilon_c(k)$. The contour error change, $\Delta\varepsilon_c(k)$, is the difference between the calculated contour error of kth sampling period and that of the $(k-1)$th sampling period. That is,

$$\Delta\varepsilon_c(k) = \varepsilon_c(k) - \varepsilon_c(k-1) \tag{3.2}$$

The output of the fuzzy controller, $\Delta F(k)$, is defined as the deviation of the feedrate command. Therefore, the feedrate command of the kth sampling period, $F(k)$, is equal to the summation of the output of the fuzzy controller of the kth sampling period, $\Delta F(k)$, and the feedrate command of the $(k-1)$th sampling period, $F(k-1)$. That is

$$F(k) = F(k-1) + \Delta F(k) \tag{3.3}$$

3.3 Fuzzy control algorithms and rules

In order to let the quantity of the real world be fuzzified to the quality of the fuzzy world, it is necessary to quantify the qualitative statement. As a result, five kinds of fuzzy linguistic variables (PB: Positive Big, PS: Positive Small, ZO: Zero, NS: Negative Small, and NB: Negative Big) are defined for each input variables, and 6 fuzzy if-then control rules are normally prepared based on human expert linguistic control rules, see Table 3.1

Table 3.1 Fuzzy control rules.

E DE	PB	PS	ZE	NS	NB
PB					
PS		PS	PB	PB	
ZE	NS				NS
NS		PB	PB	PS	
NB					

Ⅳ. Computer simulations

To demonstrate the effectiveness of the proposed fuzzy controller, computer simulations are conducted. The parameters of the X-Y servo axes used in simulations are shown in Table 4.1. The simulation model also contains nonlinear terms such as a coulomb friction, saturator, and disturbance. The parameters of controllers are shown in Table 4.2.

Fuzzy membership functions for two inputs, ε_c and $\Delta\varepsilon_c$ to FLC are five kinds for each input variables and eight fuzzy if-then control rules are prepared. The gain g_ε for the error and the gain $g_{c\varepsilon}$ for the change of contour error are scaled as contour error bound. The gain $g_{\Delta F}$ for the deviation of the feedrate command is 0.35. We compare the performance of the proposed method with that of the constant feedrate method for circle and corner contours.

Table 4.1 Parameters of X-Y servo system.

Axis	Inertia	Viscous friction	Coulomb friction	Torque constant
	$J(kg\,m^2)$	$B(Nms)$	$F_c(Nm)$	$K_t(Nm/A$
X-axis	0.0103	0.0336	0.2	1.2054
Y-axis	0.012	0.0308	0.31	

Table 4.2 Controller parameters of each axis.

	Tracking controller gains		Current controller gains	
	k_p	k_d	k_{sp}	k_{si}
X-axis	5.5	0.02	1.3	2.35
Y-axis	4.95	0.02	1.3	2.35

4.1 The circle contour

In this section, the simulation result for circle contour as a general nonlinear contour is presented. The equations for the reference are

$$\begin{aligned} P_x(t) &= R\cdot\cos\omega t \\ P_y(t) &= R\cdot\sin\omega t \end{aligned} \qquad (4.1)$$

where the radius of the circle R is 20 mm and P_x , P_y represents X, Y reference position respectively. Figure. 4.1 shows the contour error and Fig. 4.2 shows the feedrate for the circle contour. As shown in Table 4.3, the cycle time is reduced by 9.83 percent. The 200 times enlarged contouring result is shown in Fig. 4.3.

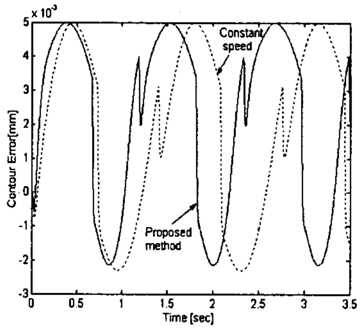

Fig. 4.1 Contour errors for the circle.

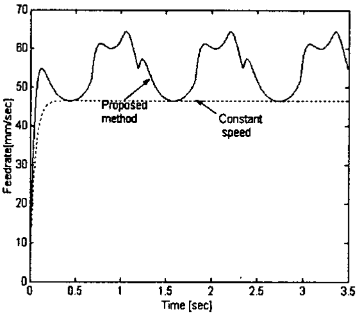

Fig. 4.2 Feedrate for the circle.

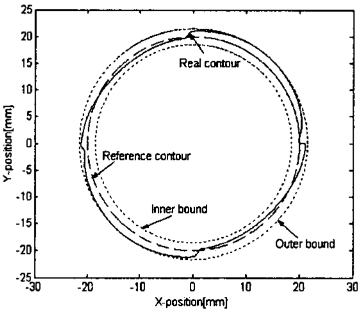

Fig. 4.3 Contouring result for the circle.

4.2 The corner contour

A simulation is carried out for the corner contour. The angle of which is changed from +45 degrees to -45 degrees. Figure. 4.4 shows the contour error of which error bound is 0.0045mm. Fig 4.5 shows the feedrate. As shown in Table 4.3, the cycle time is reduced by 9.89 percent. A 600 times enlarged contouring result is shown in Fig. 4.6, where all contour errors are bounded within the contour error bound.

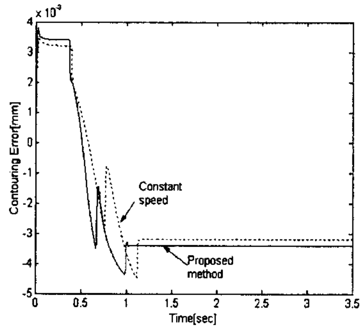

Fig. 4.4 Contour errors for the corner.

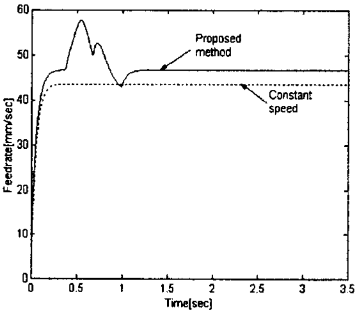

Fig. 4.5 Feedrate for the corner.

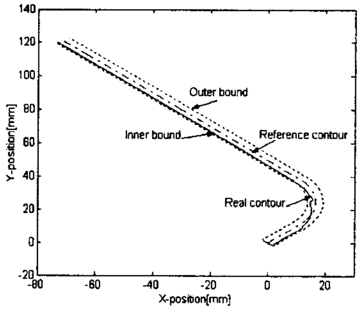

Fig. 4.6 Contouring result for the corner.

Table 4.3 Contouring response for the circle, corner.

Specification	Circle		Corner	
	Constant speed	Proposed method	Constant speed	Proposed method
$\varepsilon_{c\ peak}$ $(10^{-3} mm)$	5.00	5.00	4.476	4.360
Cycle time (sec)	2.57	2.34	1.465	1.320

V. Conclusion

A fuzzy logic controller has been proposed for feedrate control of CNC machines. It is shown that the design of the adaptive control system is simple and easy to implement in commercialized CNC machine tool. The contour error is calculated using a recent contour error model, which is flexible to all trajectories. To find faster feedrate within a tolerable error bound, fuzzy rules considering the relationship between the contour error and the feedrate are prepared. The fuzzy controller can adjust feedrate as contour error. From the simulation results, we confirm the proposed method achieves higher productivity than the conventional method while preserving high accuracy. Further research should be directed toward high-speed and high precision within the error bound.

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