

# A Fuzzy Self-tuning Controlled Feeding Servo System of Machine Tool

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## Abstract

The permanent magnet synchronous motor (PMSM) has been used widely for computer numerically controlled (CNC) feeding servo system (FSS) of machine tools. The control performance of the actual CNC-FSS depends on many parameters, and it has the properties of nonlinear uncertainty and time-varying characteristics. It is difficult to establish an accurate model for the actual CNC-FSS, therefore, a fuzzy self-tuning controller (FSC) of CNC-FSS was developed to overcome this problem in this paper. The proposed control strategy was based on fuzzy control theory combined with the conventional proportion integration differentiation (PID) control and its control algorithm. In this paper, we presented design of controller using FSC method and analyzed time response of the intelligent controller. Step response was plotted and analyzed to verify the effectiveness of the proposed controllers. Simulation results show that the FSC has minimum overshoot, minimum transient and steady state parameters, which shows the more effectiveness and efficiency of FSC than conventional PID controller to control the position of the CNC-FSS.

**Keywords:** fuzzy control, parameter adjustment, PID controller, self-tuning, CNC-FSS

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## 1. Introduction

In industrial process control, PID controller, with its simple structure and easy operation, has been widely used. However, traditional PID controller aims at the linear process with exact model, whose PID parameters cannot be adjusted once they have been determined [1]. With complex trainability, parameter variability and model uncertainty of CNC servo system, and involved with friction characteristics analysis of feeding system dynamic modeling and disturbance torque as well as parameters of mechanical damping, stiffness, inertia, etc. Conventional PID parameter tuning fails to adapt to such a complex nonlinear control system, thus affects the accuracy and reliability of machine tools [2]. The fuzzy control transforms person's experience and knowledge into the control strategy without knowing the exact mathematical model but simply empirical knowledge of the site operator to effectively control complex system, which is difficult for model to determine [3]. Although fuzzy control changes the duty cycle of PWM system, it cannot fundamentally eliminate the static error [4]. Therefore, Fuzzy and PID control is an excellent parameter optimization method, which accords to the interpersonal response of control system and the fuzzy reasoning, automatically achieves the best adjustment of PID parameters [5].

In order to better improve the control performance, meanwhile, owing to nonlinearity, degeneration and randomness of the feeding servo system, a combination of fuzzy control with traditional PID control was used in the paper, both Fuzzy control and PID control algorithms establish an intelligent control algorithm, and a fuzzy self-tuning controller was designed. The simulation results show that the system dynamic response is better when using fuzzy self-tuning PID control method, with minimum overshoot, high steady precision, better adaptability and robustness. The controller is used in servo control system of CNC machine tools, and could automatically adjust the fuzzy control parameters in the process to achieve the optimization of

control parameters, the control precision and dynamic as well as static performance of the control system are improved.

**2. Mathematical Modeling of CNC-FSS**

**2.1. Basic Components of the FSS**

As an important part of CNC machine tools, FSS is to control the displacement, direction and speed of the movement of execution units. As shown in Figure 1, this consists of mechanical transmission mechanism as well as the execution units and the electrical drive control. The former includes a table (or turret), a ball screw and a transmission gear, etc., the latter includes a motor, a drive control system, a power amplifier, and detecting element. Currently, high-precision CNC-FSS of machine tool generally employs alternating current servo system with permanent magnet synchronous motor because of its better dynamic and static performance [6]. PMSM AC servo system is mainly composed of permanent magnet synchronous servo motor, speed and position sensors, power inverter and PWM generation circuit current, position and speed controller, whereas AC motor is a strong coupling, time-varying, non-linear system with more complicated control process.

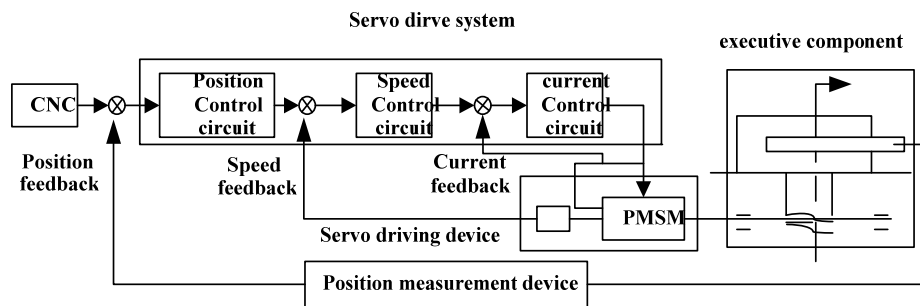


Figure 1. The composition of numerical control FSS

**2.2. Mathematical Modeling**

AC servo system mathematical modeling is shown in Figure 2, which shows that it might be indicated by the following transfer function under the field oriented control.

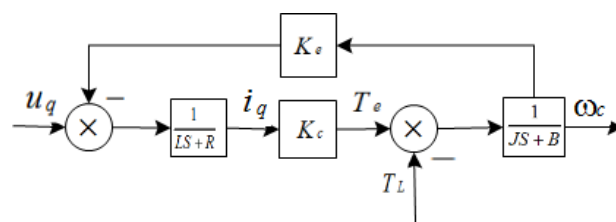


Figure 2. The diagram of PMSM feeding servo system

The formulate for AC servo system, It can be expressed as:

$$G_M(S) = \frac{K_c}{LJ S^2 + (RJ + LB)S + BR + K_c K_e} \tag{1}$$

Where:  $K_c = (3p_n \phi_f) / 2$  is motor torque coefficient;  $K_e = p_n \phi_f$  is motor back emf constant; L is motor winding inductance; R is motor coil resistance and J is total rotation inertia amount (including  $J_s$  is screw rotation inertia,  $J_1$  and  $J_2$  are gear rotation inertia between the

screw and the motor, and  $J_M$  is motor shaft rotational inertia);  $B$  is total viscous damping coefficient (including  $B_S$  is screw damping,  $B_1$  and  $B_2$  are gear rotation inertia between the screw and the motor and  $B_M$  is motor shaft damping).

**3. Design of FSC- PID**

Overall scheme of FSC- PID as shown in Figure 3. It can be seen from Figure 3, a fuzzy PID controller is formed with fuzzy control algorithm and PID control algorithm combined. The input of fuzzy inference part is deviation  $e$  and deviation change rate  $e_c$ , output is  $\Delta K_p$ ,  $\Delta K_i$  and  $\Delta K_d$ , which not only maintains the advantages of a PID controller but also adjusts the parameters of a PID controller through intellectual technology to adapt to the characteristic changes of controlled object [6].

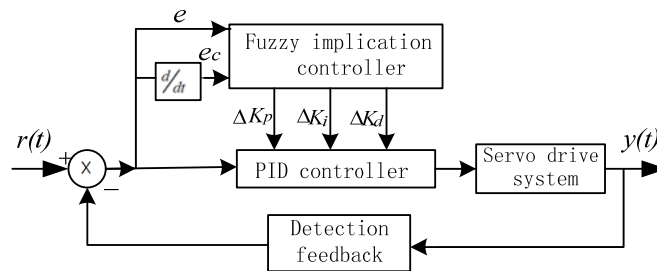


Figure 3. Overall scheme of FSC- PID

**3.1. Structures of FSC**

The first important step in the fuzzy controller design is selection of the input and output variables. In this project, position error  $e$  and position error change  $e_c$  are selected as input variable whereas the output variable are  $\Delta K_p$ ,  $\Delta K_i$  and  $\Delta K_d$ . Different part of fuzzy controller such as selection of membership functions, fuzzy control rules and etc. are explained in the next sections.

**3.2. Membership Functions**

Fuzzy sets must be defined for each input and output variable. As shown in Figure 4. Five fuzzy subsets PL (Positive Large), PM (Positive Medium), ZE (Zero), NL (Negative Large), NM (Negative Medium) have been chosen for position error  $e$  and position error change  $e_c$  as input variables. Also three  $\Delta K_p$ ,  $\Delta K_i$  and  $\Delta K_d$ , have been selected for the output linguistic variables. For the output variable five fuzzy subsets have been used (PL, PM, ZE, NM, NL), in order to smooth the control action. As shown in Figure 4 and Figure 5, triangular shapes have been adopted for the membership functions; the value of each input and output variable is normalized in  $[-6, 6]$  by using suitable scale factors.

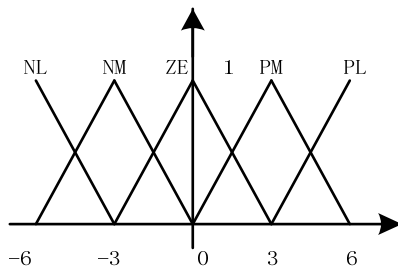


Figure 4. The membership functions of  $e$  and  $e_c$

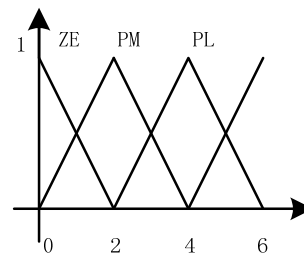


Figure 5. The membership functions of  $\Delta K_p$ ,  $\Delta K_i$  and  $\Delta K_d$

### 3.3. Fuzzy control rules

To establish the formulate for derivation of control rules FSC-PID, the assumptions adopted are as follows:

$$K_p = K'_p + \Delta K_p \quad (2)$$

$$K_i = K'_i + \Delta K_i \quad (3)$$

$$K_d = K'_d + \Delta K_d \quad (4)$$

Where:  $K'_p$ ,  $K'_i$  and  $K'_d$  are initial value of PID parameters;  $\Delta K_p$ ,  $\Delta K_i$  and  $\Delta K_d$  for fuzzy controller output;  $K_p$ ,  $K_i$  and  $K_d$  are ultimate control output.

Usually, according to traditional PID control theory, the formula of incremental algorithm can be obtained. One may write as follow:

$$U(k) = K_p e(k) + K_i \sum e(k) + K_d e_c(k) \quad (5)$$

Where :

$$\sum e(k) = e(k) + e(k-1) \quad (6)$$

$$e_c(k) = e(k) - e(k-1) \quad (7)$$

are deviations and their change of input variables respectively, and  $K_p$ ,  $K_i$  and  $K_d$  are parameters for their proportional, integral and derivative actions. Proportional coefficient  $K_p$  is to accelerate response speed of the system to improve regulating accuracy of the system, where the greater  $K_p$ , the faster response speed and the higher regulation accuracy. But if it is too great, it will overshoot, and even lead to system instability. Integral coefficient  $K_i$  is to eliminate system steady-state error, where the greater  $K_i$ , the faster static differential elimination. But if it is too great, it will cause integral saturation and lead to larger overshoot. Differential coefficient  $K_d$  impacts dynamic characteristics of the system, where the greater  $K_d$ , the more it can suppress the deviation change. But if too great, it will extend regulating time and reduce anti-interference ability. In accordance with the impacts of parameters  $K_p$ ,  $K_i$  and  $K_d$  to output characteristics of the system [7].  $K_p$ ,  $K_i$  and  $K_d$  self-tuning principles can be summarized for different  $e$  and  $e_c$  in the system control process:

a. when  $|e|$  is small, for better tracking performance of the system, larger  $K_p$  and smaller  $K_d$ , should be available, and simultaneously integral role should be limited, usually  $K_i = 0$ , to avoid larger system response overshoot.

b. when  $|e|$  and  $|e_c|$  are medium, in order to reduce system response overshoot and guarantee a certain response speed, smaller  $K_p$  should be available. In this case, smaller  $K_d$  and appropriate  $K_i$  should be available.

c. when  $|e|$  is small, for better steady-state performance of the system,  $K_p$  and  $K_i$  should be increased, and  $K_d$  should be selected properly to avoid output response oscillation at the set value and take anti-interference ability of the system into consideration. The principle should be followed as: when deviation change rate is smaller, greater  $K_d$  is available; when it is larger, smaller  $K_d$ , usually the medium size.

From the above analysis, principles and accumulated practical experience to adjust according to the the PID parameters described, it can get the output variable  $K_p$ ,  $K_i$  and  $K_d$  control rule tables as shown in Table 1, Table 2 and Table 3.

They show the changes of the values of  $K_p$ ,  $K_i$  and  $K_d$  of the system error  $e$  and error change  $e_c$  variation in different circumstances from Tables, and shown error and error change when negative value corresponding to NL, NM and NS; and shown error and error variation corresponding positive PS, PM and PL, respectively, to take positive or negative error and error change variation larger, the variation of error and error change variation large.

Table 1. The control rules of  $K_p$

$K_p \backslash e \backslash e_c$	NL	NM	NS	ZE	PS	PM	PL
NL	PL	PL	PM	PM	PS	ZE	ZE
NM	PL	PL	PM	PS	PS	ZE	NS
NS	PM	PM	PM	PS	ZE	NS	NS
ZE	PM	PM	PS	ZE	NS	NM	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NS	NM	NM	NM	NL
PL	ZE	ZE	NM	NM	NM	NL	NL

Table 2 . The control rules of  $K_i$

$K_i \backslash e \backslash e_c$	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	ZE	ZE
NM	NL	NL	NM	NS	NS	ZE	ZE
NS	NL	NM	NS	NS	ZE	PS	PS
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PL
PM	ZE	ZE	PS	PS	PM	PL	PL
PL	ZE	ZE	PS	PM	PM	PL	PL

**3.4. Establish Structure of Fuzzy Controller**

When typing Fuzzy into MATLAB command window, the FIS editor interface occurs, then it can easily edit the fuzzy inference system, selecting Madmen type for controller type, min for AND, max for OR, min for inference, max for aggregation, and center of gravity average method for DEFUZZIFICATION. And open drop-down menu edit of FIS editor, and then select input and output variables in the Add Variable. Finally, according to table 1, table 2 and table 3, fuzzy control rule can be drawn as the following when inputting fuzzy control rules under the Rules of the edit form:

- If ( $e$  is NL) and ( $e_c$  is NL) then ( $K_p$  is PL) ( $K_i$  is NL) ( $K_d$  is PS)
- If ( $e$  is NL) and ( $e_c$  is NM) then ( $K_p$  is PL) ( $K_i$  is NL) ( $K_d$  is NS)
- If ( $e$  is NL) and ( $e_c$  is NS) then ( $K_p$  is PM) ( $K_i$  is NM) ( $K_d$  is NL)
- If ( $e$  is NL) and ( $e_c$  is ZE) then ( $K_p$  is PM) ( $K_i$  is NM) ( $K_d$  is NL)
- If ( $e$  is NL) and ( $e_c$  is PS) then ( $K_p$  is PS) ( $K_i$  is NS) ( $K_d$  is NL)
- .....

After having established a fuzzy controller, kept them, and saved to workspace submenu into a memory buffer, so called up in the simulink simulation platform. At this point, a file named as NH. FIS is established to complete the overall structure of fuzzy controller.

**3.5. PID Controller of Fuzzy Self-Tuning**

After having established fuzzy controller, the conventional PID controller incremental algorithm according to equations (2), (3) and (4) combined with self-tuning PID parameter calculation equations(5), (6) and (7), can be establish fuzzy self-tuning PID controller in the SIMULINK environment, as shown in figure 6.

**4. Results and Analysis**

**4.1. Simulation of CNC- FSS**

From the above formula (1) and Siemens motor model IFKI602, we select Z-axis feeding servo system of a CNC machine tool for simulation research, whose workbench quality is  $M=3500\text{kg}$ , lead screw  $L=0.0012\text{m}$ , screw total length  $Z=0.963\text{m}$ , screw supporting axial stiffness  $K_B=1.12 \times 10^8 \text{ N/m}$ , screw nut contact stiffness  $K_N=2.02 \times 10^8 \text{ N/m}$ , and motor moment of inertia  $J=0.01323\text{kg} \cdot \text{m}^2$ . Based on the above parameters, transfer function of the electromechanical coupling system was determined, and then a simulation diagram for fuzzy self-tuning PID control was established as shown in Figure 7.

Table 3. The control rules of  $K_d$

$K_d \backslash e_c$	NL	NM	NS	ZE	PS	PM	PL
NL	PS	NS	NL	NL	NL	NM	PS
NM	PS	NS	NL	NM	NM	NS	ZE
NS	ZE	NS	NM	NM	NS	NS	ZE
ZE	ZE	NS	NS	NS	NS	NS	ZE
PS	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PM	PL	NS	PS	PS	PS	PS	PL
PL	PL	PM	PM	PM	PS	PS	PL

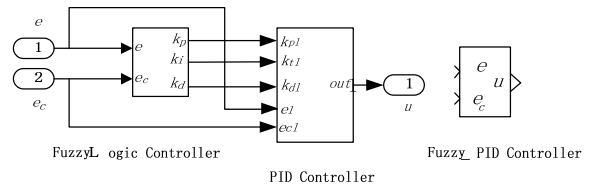


Figure 6. Fuzzy self-tuning PID controller

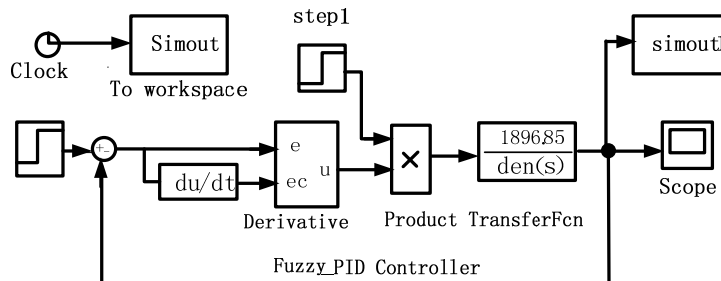


Figure 7. Simulation of CNC-FSS

**4.2. Analysis Both of Controller Performance**

According to equations (2), (3) and (4) and set the parameters of traditional PID the controller for experiment of comparative study in the SIMULINK environment. Therefore, we have chosen quantifiable factor  $K_e = 0.2$ ,  $K_{ec} = 0.1$ , defuzzifier factor  $k_1=0.5$ ,  $k_2 = 0.01$ ,  $k_3 = 0.01$ , three initial values of PID controller  $K'_p = 16.4$ ,  $K'_i = 0.3$ ,  $K'_d = 0.5$ . Assuming that the system input is a step signal of the amplitude of 1, in order to test the robustness of fuzzy PID controller, an interference with amplitude of 0.1 is added respectively at the 0.8s in accordance with fuzzy PID control method and traditional PID control method. Simulation result is shown in Figure 8. It can be seen that the system dynamic response curve is better when using fuzzy self-tuning PID control method, with minimum overshoot, high steady precision, better adaptability and robustness. Therefore, the system dynamic performance has been improved comprehensively and its anti-interference ability has been improved as well.

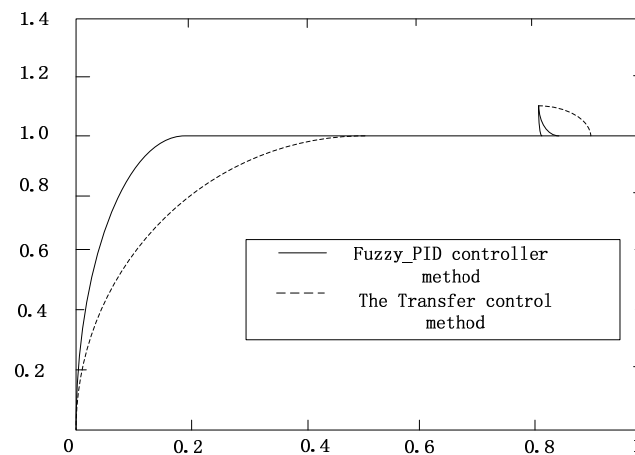


Figure 8. Both of controller performance comparison

## 5. Conclusion

A new method to improve the accuracy of FSC-PID controller CNC-FSS of machine tools was proposed in the paper, and PID controller was designed. The FSC-PID controller applied considers electromechanical coupling effect, and it can change according to the deviation with the deviation of the measure date, online self-tuning the three parameters of the PID controller. The simulation and experimental results show that the fuzzy approach has minimum overshoot, minimum transient, steady state parameters and dynamic response.

From this paper, several conclusions can be drawn: firstly, the FSC-PID controller would be able to respond to the system's nonlinear and time-varying behaviors, it would not be required to establish the precise mathematical model of controlled CNC-FSS. By adjusting the control parameters, it can adapt to different controlled object, and therefore has strong adaptability. Secondly, the method can make the mechanical parts to reach  $1\mu\text{m}$  level in the CNC machine tools process. Thirdly, improving the anti-jamming system performance can adapt to the dynamic performance requirements in a different state of the CNC-FSS, to solve the stage of CNC machine tools rough and final stages of conversion, to be able to control the machining accuracy of the workpiece.

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