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Abstract: Micro-linear motor, is the key feed components which is based on macro–micro-motion control technology, the accuracy of its movement directly determines the accuracy of ultra-precision machining level. Based on the study of the open servo characteristics of POWER program multiple axis controller (PMAC), a fuzzy proportional integral derivative (PID) composite control technology is applied to the servo control of the motor. The fuzzy control is used to improve the response speed and accuracy of the motor. However, the system is difficult to control when the load is changed. To solve this problem, a precise PID control is used to realize precise position control. In this study, the position of the motor is analyzed based on the analysis of linear motor installation and load characteristics, the use of smooth switching fuzzy PID composite control algorithm is implemented to the micro-feed motor control. Due to the introduction of the smoothing weighting function, the composite fuzzy PID servo control mode of dual mode switching is implemented without disturbance switching. Finally, the effect of the control algorithm is verified by experiments, especially in the case of small errors, this algorithm still reflects the ability to adapt to the impact of interference.

1 Introduction

Micro-linear motor, is the key feed components which is based on macro–micro-motion control technology, the accuracy of its movement directly determines the accuracy of ultra-precision machining level. Therefore, the performance of the servo system directly affects the positioning accuracy and trajectory tracking accuracy of the machine tools, and which ultimately affects the processing quality of the processing products. The adoption of good control strategy is an important technical means to improve the performance of the servo system. As the combination control of classic control with quantitative calculation control strategy and intelligent control with qualitative reasoning control becomes the focus of research [1–3], the research of fuzzy proportional integral derivative (PID) control and its application in AC–DC servo system are also increasingly improved. There are many types of fuzzy PID control strategies, such as fuzzy PID parameter self-tuning control and fuzzy PID compound control [4–7].

The linear servo system adopts the direct drive mode, which makes the system have fast dynamic characteristics, simple structure, wide speed range and precise positioning. However, the influence of uncertainties, such as system parameter perturbation and load disturbance, caused by direct driving will be directly reflected in the static and dynamic characteristics of the precision feeding micro-linear motor system without any buffering in the middle. Therefore, the emergence of these uncertainties further increases the control difficulty that make the system non-linearity becomes more obvious, so when it is difficult to establish an accurate mathematical model [8]. The mechanical simplification of the micro-linear motor servo feed system has led to the complexity of the control system. Therefore, traditional or modern control technology based on the mathematical model of the system is difficult to control the micro-linear servo system [9]. Therefore, it is necessary to adopt a more effective control technology than that of the rotary electric machine. With the development of the times, the requirements on the servo system are getting higher and higher. The intelligent control is introduced into the micro-linear servo system, and the system has higher performance index. It is an effective way to improve the performance of the linear servo system [10]. In the current linear motor control applications, although PID control is still the mainstream control strategy [11–14], the research, development and application of fuzzy technology have proved that the fuzzy PID compound control can make the linear motor control get better servo dynamic characteristics [15–18].

Fuzzy control is a control method based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning, and it belongs to the category of intelligent control. It has the characteristics of knowledge expression and does not depend on the mathematical model of the object. Through the fuzzy logic and fuzzy reasoning, it makes experience become a control rule to do effective real-time control. PID is a traditional control technology. Due to its mature technology, good stability, high reliability and control precision, PID is still the most basic control form of AC servo motor [18]. There are many ways to tune PID parameters, but they are generally based on object characteristics. Fuzzy PID control technology will be advanced fuzzy control and classical PID control together, both advantages are complementary. Especially for the micro-linear motor drive and control, it is often influenced by external disturbances, load changes and magnetic field distortions during operation. The introduction of intelligent fuzzy control can change the output driving state of the motor in time to increase the stability of the reaction and the accuracy of positioning [19].

In this paper, fuzzy PID composite controller is used instead of the built-in PID controller for micro-linear motor servo control. The fuzzy control is used to improve the dynamic performance of the servo system, and the improved PID control algorithm is used to improve the servo accuracy and reduce the tracking error.

2 Micro-linear motor servo control hardware structure

The linear motor used in this project includes the motion controller, driver, micro-linear motor and grating position detection components, but the control principle is not exactly the same, as shown in Fig. 1.
The design of the control algorithm is implemented by Turbo PMAC motion controller. For the servo motor, the control speed loop is closed on the drive. For linear motor control, the current loop is closed on the drive. So the design of the control algorithm in the motion controller must take into account the control that the drive already has to make the servo control overall good. In this paper, the controller designed is directly embedded in the Turbo PMAC to realise the servo control of the motor. It does not include the control algorithm that the driver already has.

3 Design and experiment of fuzzy PID dual-mode controller

Fuzzy controller is a kind of non-linear control. According to the file processing, using the query decision table method, the input amount needs to be rounded or rounding, there is quantisation error and static residuals, resulting in the control accuracy decreases. The traditional PID control can greatly improve the control accuracy and eliminate the steady-state error. The main idea of fuzzy PID composite control is to make full use of the control characteristics of the two, to improve the dynamic performance in the case of large error using fuzzy control and to use PID to realise precise control in the small error state.

3.1 Improved PID controller

PID is a deviation controller, the role of the premise is that the controlled amount must deviate from the set value. The controlled amount needs to be rounded or rounding, there is quantisation error and static residuals, resulting in the control accuracy decreases. Therefore, in principle, this feedforward control is an ideal control method, which is much better than a closed-loop system based on error control alone. However, it is impossible to realise such idealised composite control completely. On the one hand, the linear range of the actual system is limited. On the other hand, the design of high-order differential devices is very difficult, and the higher the differential order is, the more sensitive the input noise is, but the worse the operating characteristics of the system. Usually feedforward device differential order of 2 can get satisfactory results.

In PID control, the feedforward of speed and acceleration are introduced to form first-order and second-order feedforward devices. The control structure in Fig. 3 is an improved PID controller with feedforward. The speed feedforward of the controller can obviously improve the servo tracking accuracy of the system.

3.2 Specific design of fuzzy controller

Fuzzy controller uses double input and single output model, the input is error $E$ and error rate of change $EC$, and the output is decision control variable $U$. The fuzzy subset of linguistic values of language variables $E$, $EC$ and $U$ are

$$E : \{ NB, NM, NS, ZE, PS, PM, PB \};$$
$$EC : \{ NB, NM, NS, ZE, PS, PM, PB \};$$
$$U : \{ NB, NM, NS, ZE, PS, PM, PB \};$$

Domain levels are:

$$E : \{ -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6 \};$$
$$EC : \{ -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6 \};$$
$$U : \{ -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6 \};$$

The degree of overlap between the membership functions of fuzzy sets directly affects the performance of the system. Based on experience, the distribution lists of membership values for each language value of $E$, $EC$, and $U$ are determined. According to the input and output fuzzy subsets of fuzzifier, the fuzzy rules are established by using the conventional fuzzy conditions and the fuzzy relation ‘IF A AND B THEN C’ to form the fuzzy algorithm which describes the control process. The final fuzzy rules show in Table 1.

Table 1 can be written in the sentence format as

$$\text{If } E = A_i \text{ and } EC = B_j \text{ then } U = C_{ij} \text{ where } i = 1, 2, 3, 4, 5, 6, 7 \text{ and } j = 1, 2, 3, 4, 5, 6, 7.$$ 

$$\text{If } E = A_i \text{ and } EC = B_j, \text{ then } U = C_{ij} \text{ where } i = 1, 2, 3, 4, 5, 6, 7 \text{ and } j = 1, 2, 3, 4, 5, 6, 7.$$ 

According to fuzzy reasoning synthesis rules can be obtained control $U$:

$$U = (E \times EC) \times R \quad (1)$$
The membership function of $U$ is
\[ \mu_U(z) = \bigvee_{x \in E, y \in EC} \mu_R(x, y, z) \land \mu_E(x) \land \mu_EC(y) \] (2)

### 3.3 Dual-mode switching fuzzy PID composite control

As shown in Fig. 4, $e_v$ is the error threshold, and fuzzy control is used in the range of large deviation ($|e| > e_v$) to get good dynamic performance. In the small deviation ($|e| \leq e_v$), PID control eliminates the system's steady-state error and improves the servo tracking accuracy.

According to the above controller design of improving PID algorithm and fuzzy control algorithm, fuzzy PID composite controller control experiment is carried out on PRS-XY numerical control system. In the experiment, the servo cycle is fixed at 0.442 ms. The adjusted PID parameters and the main related parameters are shown in Table 2. The PID parameters are normalised according to the parameters of the Turbo PMAC and stored in the default variables for switching with the built-in PID algorithm.

### 4 Experiment

In the experiment, take the error threshold $e_v = 0.05$ mm, and take No. 2 micro-linear motor and the servomotor with worktable X as the object. Servo period is 0.442 ms. In the step response test, the step distance is 1 mm (10,000 cts), and one-way time is 500 ms. The experimental results are shown in Figs. 5 and 6. In the following the error test, a parabolic trajectory as shown in Fig. 7 was used with a one-way travel of 1 mm and a one-way time of 500 ms. The testing software is PMAC Tuning Pro software of Delta Tau company [22]. Linear motor experimental results are shown in Fig. 8.

The main performance evaluation parameters of the micro-linear motor obtained in the experiment are listed in Table 3.
The experimental results show that the switch-switched fuzzy PID control improves the dynamic characteristics of servo control. Especially for the control of the servo motor with the worktable, in addition to the motor commutation, its follow-up error is in the range of $-1$–$2 \mu m$, which basically maintain an ideal state. The experimental results meet the requirements of high precision servo tracking. For the micro-linear motor, although the dynamic performance is obviously improved, the follow-up error is still not ideal, and there is error fluctuation in the adjustment process.

5 Conclusion

In this paper, the fuzzy PID composite control technology is applied to the servo control of the motor. The fuzzy control is used to improve the response speed and dynamic performance of the system, and the improved PID control is used to realise precise position control. Adopting the dual-mode control made of improved PID and fuzzy PID improves the control switching process and further improves the servo tracking precision of the micro-linear motor.

6 Acknowledgment

This paper is supported by TUTE Scientific Research Found(KJ14-16) &(KJ1810); The key technologies R&D program of Tianjin(17KPXMMSF00180) – Delta parallel man–machine robot science system development; The key technologies R&D program of Tianjin (17YFCZZC00270) – Development of Key Technology for Semi-physical Simulation System and Cloud Service Platform of High-end CNC Machine Tools; Innovation and entrepreneurship training program for College Students of Tianjin University of Technology and Education (20171006124) – Mechanical modelling and error analysis of vehicle milling complex machine tool.

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