Fuzzy PID Control of the Planar Switched Reluctance Motor for Precision Positioning

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Abstract-This paper proposes a fuzzy proportional-integral-derivative (PID) control for the planar switched reluctance motor (PSRM) to realize precision positioning. The mathematical model of the PSRM is first given. Then a fuzzy proportional-derivative (PD) controller is designed for the PSRM, which features strong robustness to parametric variation, uncertainty, and interference. The fuzzy PD control of the PSRM is carried out via simulation based on MATLAB. Compared with the PD controller, the control performance of the PSRM with the fuzzy PD controller is superior. The effectiveness of the proposed control is verified through the simulation results.

Keywords-Fuzzy PID control; Precision positioning; Planar switched reluctance motor.

I. INTRODUCTION

The precision positioning of actuators is playing an important role in modern industry, such as semiconductor lithography and scanning microscope. Compared to actuators achieving two-dimension motion with complicated mechanical transmissions, planar motors are particularly attractive due to direct drive, low friction, and no backlash [1], [2]. The planar switched reluctance motor (PSRM), which is one kind of the planar motors, has the features of simple structure, low cost, low heat loss, high reliability, and high precision [3], [4]. However, it is challenging to achieve precision positioning for the PSRM owing to its high nonlinearity and large force ripple.

For the operated PSRM, its inductance is time-varying and an uncertainty caused by the large friction always exists. Thus, a position control, which features strong robustness to parametric variation, uncertainty, and interference, is in high demand for the precision PSRM. Several controls have been proposed to the PSRM, including the sliding mode control [5], the adaptive control [6] and the dual-loop robust control [7]. However, these controls have not yet solved the problem of precision positioning for the PSRM with large parametric variation, uncertainty, and interference. Fuzzy proportional-integral-derivative (PID) control, which combines fuzzy control with PID control, continuously adjusts the parameters of PID control according to the time-varying operating condition to achieve the optimal performance [8], [9]. Fuzzy PID control is thus found to be suitable for the PSRM, because its strong robustness to large parametric variation, uncertainty, and interference, and easy implementation [10], [11].

In this paper, a fuzzy PID control is proposed for the PSRM to achieve precision positioning. This paper is organized as follows. In Section II, the mathematical model of the PSRM is presented. In Section III, the fuzzy PD controller of the PSRM is designed. Simulation is performed and simulation results is illustrated and analyzed for the PSRM with the fuzzy PID controller in Section IV. Finally, conclusion remarks are drawn in Section V.

II. MATHEMATICAL MODELING

The motion model of the *X-axis* or *Y-axis* of the PSRM which is developed in our laboratory can be simplified as shown in Fig. 1.

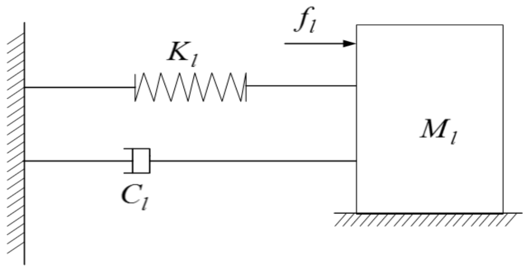

Fig. 1: The motion model of the axis of the PSRM

The kinematical equation of the PSRM can be given:

$$F_l(t) - f_l(t) = M_l \frac{d^2 x_l(t)}{dt^2} + C_l(x)\frac{dx_l(t)}{dt} + K_l(x)x_l(t) \qquad (1)$$
$$l = X, Y$$

where $F_l(\mathrm{t})$, $f_l(t)$, M_l, $C_l(x)$ and $K_l(x)$ are the thrust force, the resistance, the mass of moving platform , the friction, and the Elastic coefficient, respectively.

Ignoring the resistance to elastic deformation because of the nature of direct-drive and in the case of that $C_l(x)$ and $K_l(x)$ are invariable, the transfer function of thrust force input and position output is expressed as:

$$G_l(s) = \frac{x_l(s)}{F_l(s)} = \frac{L}{M_l s^2 + C_l s} \qquad (2)$$
$$l = X, \text{ Y}$$

where $\boldsymbol{L}$=1000 is the transformation coefficient of the unit (Meter-millimeter).

From (2), the motion system of the PSRM can be approximately equivalent to the second order system. For the PSRM which is developed independently by the laboratory, $\boldsymbol{L}$ is known and the quality M_l can be obtained by measurement. In the previous work the least square method is used to identify the system parameter C_l of the PSRM and the transfer function of the system can be obtained:

$$G_X(s) = \frac{173.6473}{s^2 + 8.3818s} \tag{3}$$

$$G_Y(s) = \frac{67.7342}{s^2 + 10.4145s} \tag{4}$$

From (3) and (4), The transmission function of both *X-axis* and *Y-axis* has a zero open-loop pole, which leads to the critical stability of the open loop system for the PSRM. Using MATLAB to simulate the transfer function, the unit step response curve of the *X-axis* and *Y-axis* is shown in Fig. 2 and Fig. 3. The system is diverging and the controller must be introduced to stabilize the system.

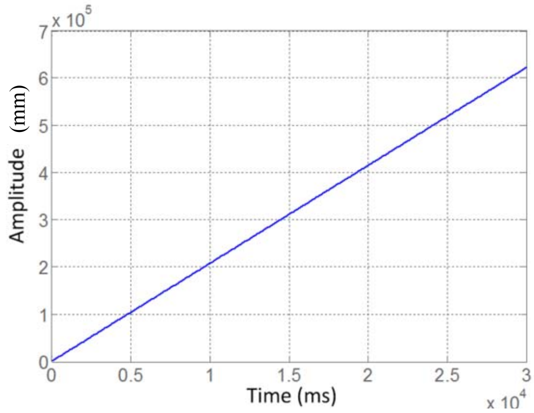

Fig. 2: Step response of *X*-axis

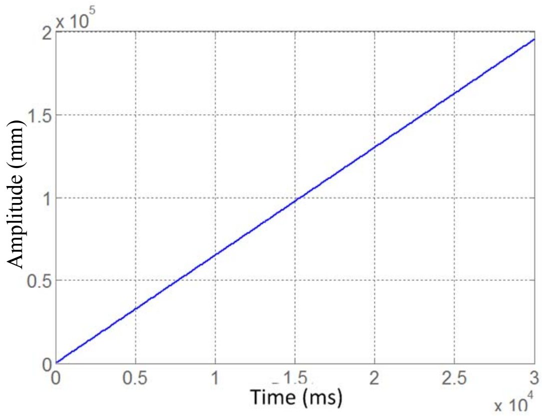

Fig. 3: Step response of *Y*-axis

III. Fuzzy PD Controller

Here is the fuzzy PD controller combines fuzzy control and classical control theory, which is designed for the PSRM. The structured block diagram (SBD) of fuzzy PD controller is shown in Fig. 4.

The input of fuzzy PD controller are error *e* and error change rate *ec,* after fuzzy processing, output *ΔKp* and *ΔKd* which make the PD controller can adjust its own parameters according to the different error and error rate of system (5), (6).

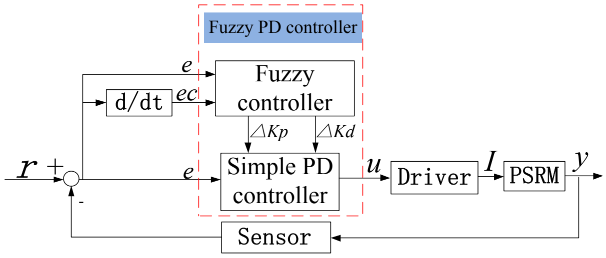

Fig. 4: Block diagram of the fuzzy PID controller

$$K_p = K_{p0} + \Delta K_p \tag{5}$$

$$K_d = K_{d0} + \Delta K_d \tag{6}$$

where K_{p0} and K_{d0} are primitive parameters of PD controller, ΔK_p and ΔK_d are the output of fuzzy controller.

According to the actual situation, *e*, *ec*, *ΔKp*, *ΔKd* are quantized [-6, 6], [-6, 6], [-6, 6], [-0.06, 0.06] region. Input and output variables are selected Triangle membership function. Using MATLAB to design the Mandani fuzzy controller and the membership function of each fuzzy subset was obtained in Fig. 5 and Fig. 6.

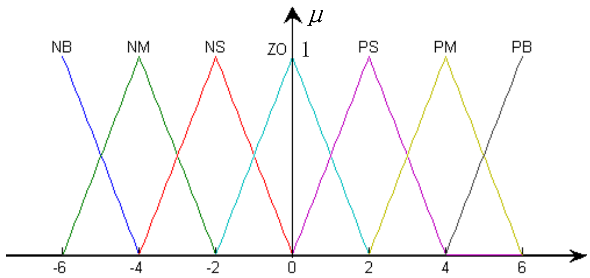

Fig. 5: Membership functions of *e* and *ec*

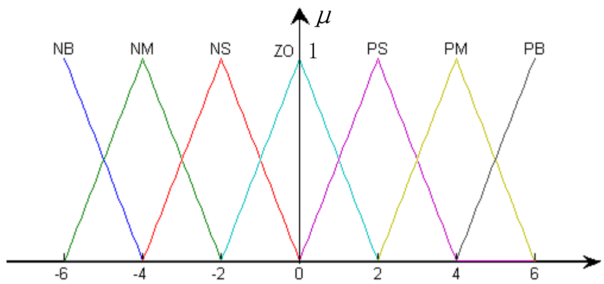

Fig. 6: Membership functions of ΔKp and ΔKd

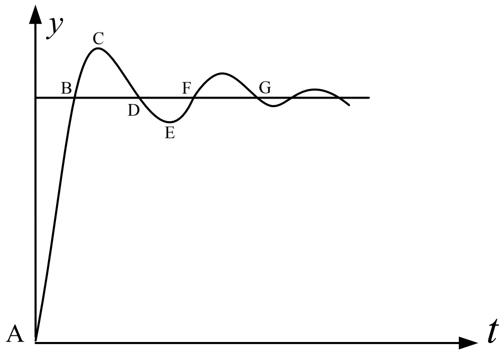

Fig. 7: Step response of a second-order system

As the step response curve of second order-system showed in Fig. 7 and summarized actual operating experience, from A to B, the error e is larger and the larger *Kp* should be selected for the acceleration system response, the smaller *Kd* should be used to avoid the differential saturation, the *Kp* in B to C should be decreased in order to reduce the overshoot, and the *Kd* should choose a moderate value. While the system error decreases (C to D), the *Kp* should decrease as the error decreases, the last in D to E, the error is increasing in the opposite direction and the *Kp* should be improved appropriately. The *ΔKp*, *ΔKd* fuzzy control rules is shown in Table 1, Table 2 respectively.

Table 1: Fuzzy control rules of *ΔKp*

e / *ec*	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 2: Fuzzy control rules of *ΔKd*

e / *ec*	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZP
NS	ZO	NS	NM	NM	NS	NS	ZP
ZO	ZO	NS	NS	NS	NS	NS	ZP
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZP
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

Defuzzification is done here using Center of Gravity (CoG) method. According to CoG defuzzification, the crisp value of scaled control output U of fuzzy PD controller can be found by

$$\mathrm{U} = \frac{\int u\mu(u)\,du}{\int \mu(u)\,du} \tag{7}$$

where: u is the scale factor.

Fig.8 and Fig.9 shows that The $\triangle Kp$ and $\triangle Kd$ changes with the error and error rate after fuzzy processing.

IV. Simulation Results

For the control system of the PSRM with the fuzzy PD controller simulation is performed based on MATLAB/Simulink. As Fig. 10 showed, here is the simulation framework of the controller.

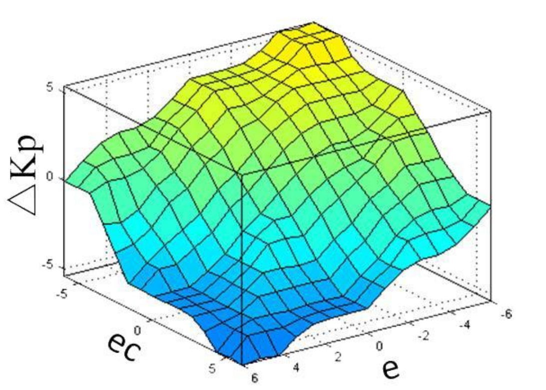

Fig. 8: $\triangle Kp$ versus *e* versus *ec*

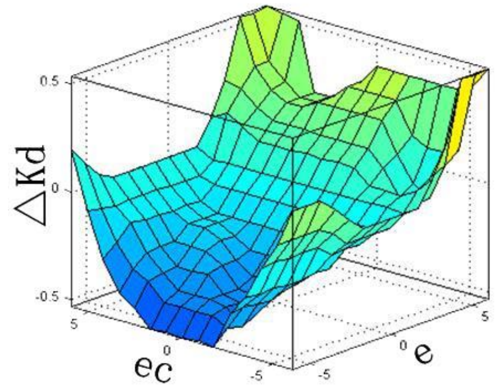

Fig. 9: $\triangle Kd$ versus *e* versus *ec*

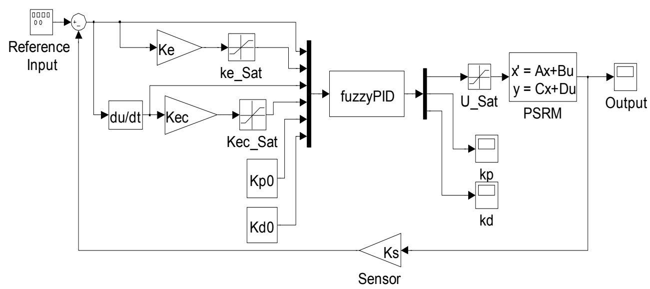

Fig. 10: Simulation system of the PSRM system with the fuzzy PD controller

Choose a square wave signal which period is 8 seconds amplitude is 15millimeters as the input signal, the initial value was set *Kp0*=20, *Kd0*=0.6 for the fuzzy PD control simulation system.

From Fig. 11 to Fig. 12, The PSRM had a better dynamic performance and steady-state performance, Due to which can quickly and accurately track the signal input and steady-state error of the control system was close to zero.

Fig. 13 and Fig. 14 shows that Proportional coefficient (*Kp*) and differential coefficient (*Kd*) of the PD controller can adaptively adjust according to the error and error rate, which made approach to the optimal control performance.

Fig. 15 shows that compared with the traditional PD controller, the fuzzy PD controller has a faster response speed and a small amount of overshoot and the steady state error is closed to zero, as the same as the traditional PD controller.

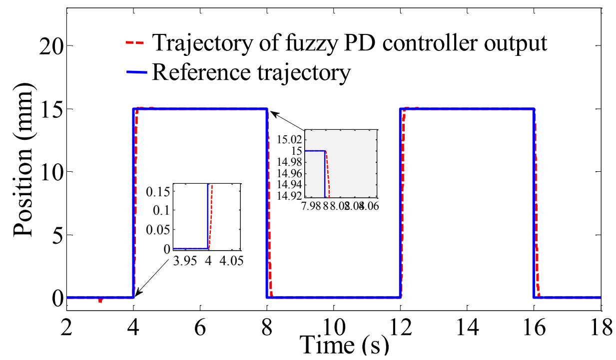

Fig. 11: Position response of the rectangular-wave

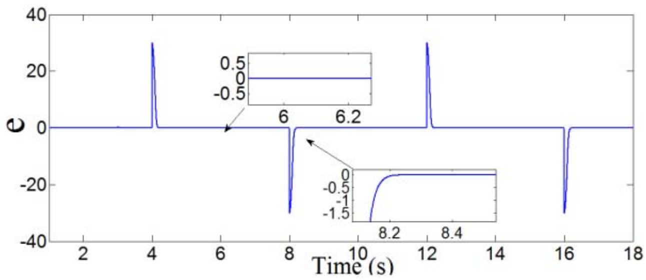

Fig. 12: Position error of the rectangular-wave

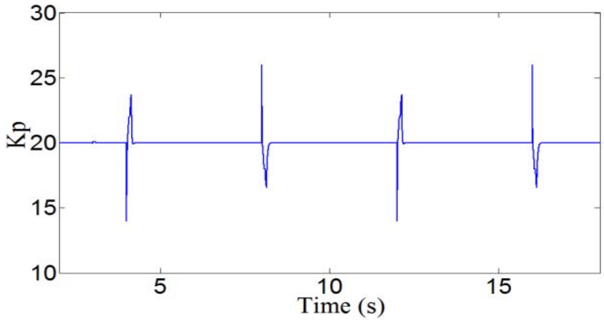

Fig. 13: *Kp*

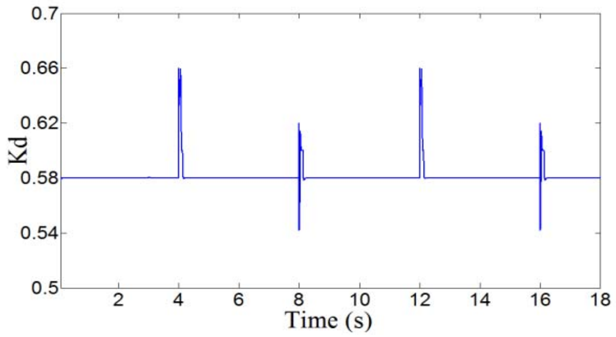

Fig. 14: *Kd*

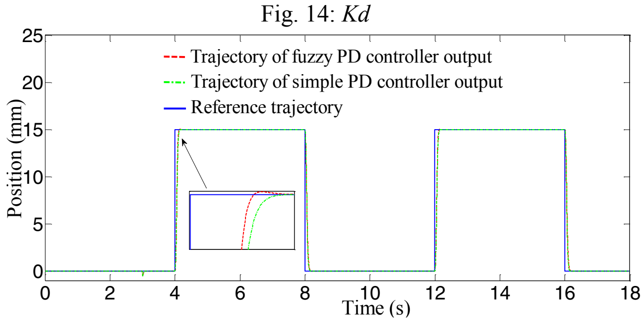

Fig. 15: Position response of the rectangular-wave

IV. CONCLUSION

This paper proposed the fuzzy PID control of the PSRM to realize precision positioning. Using the theories of fuzzy control and PID control, the fuzzy PD controller was designed for the PSRM. Simulation results show that the control performance of the PSRM with the fuzzy PD control is superior to that with the PD controller; the PSRM achieves quick response, accuracy positioning, and strong robustness to parametric variation, uncertainty, and interference. The proposed fuzzy PID control is effective for the PSRM. The future work will be focused on the experiments of this proposed control of the PSRM.

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