Position Control of Linear Servo System Using Intelligent Feedback Controller

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Abstract **- This paper presents a new position tracking control strategy that meets the position tracking performance and the closed loop robustness to external disturbance and model parameters variations without parameter identification. In order to achieve the desired input-output tracking and disturbance rejection performance independently, a two-degree-of-freedom (2DOF) internal model control (IMC) is introduced in controller structure. Furthermore, based on fuzzy logic, the parameter of the feedback controller is adjusted on-line to improve robustness. The simulation results on a direct-drive permanent magnet linear synchronous motor (PMLSM) show that proposed method is effective on improving system robustness.**

Index Terms - intelligent control, two-degree-of-freedom, motion control, position servo, PMLSM.

I. INTRODUCTION

In the field of industrial drive applications, especially in machine tools, linear movement is mostly realized by rotating motors in combination with translation mechanisms. However, these mechanical transmission chains have various problems: backlash, wear, rigid and fabrication. Using direct-drive permanent magnet linear synchronous motor (PMLSM), the effects of mechanical transmission chains can be avoid due to high electromagnetism actuate thrust, small electrical time-constant, low loss, low noise, and long move distance. Thereby, the PMLSM is usually adopted to realize micro-feed, high-speed and high-precision in servo system. It is, however, well known that the control performance of the PMLSM is sensitively to the load disturbance and mass variation because the motor mover drives directly moving part. Thus, it seems especially important to adopt a certain control strategy to achieve the satisfying servo performance.

Position-tracking servo systems require not only fine tracking performance, but also strong robust performance of disturbance rejection and load parameters variation. However, there is usually a compromise between them in a one-degree-of-freedom (1DOF) control system based on conventional proportional-integral-derivative (PID) control. In contrast, a two-degree-of-freedom (2DOF) control system specifies the reference input and the plant output separately by designing a suitable feedback and feedforward controller, respectively. The 2DOF structure improves the performance of the conventional internal model control (IMC) [1], [3], [6]. But the IMC is required to know the structure of the plant, moreover, when the parameters of plant vary, robust performance will be reduced. To overcome these problems, various robust control strategies are used in IMC system such as sliding mode, H_∞ and intelligent adaptive internal model control [2], [3], [4], [7], [8], [9]. However, the dynamic performance is affected in high-speed position servo system due to the computational complexity of the arithmetic. In this paper, a controller based on intelligent internal model control, embedded with fuzzy logic is proposed to improve tracking performance and robust performance without parameter identification.

II. INTERNAL MODEL CONTROL SYSTEM

Fig. 1 shows the basic structure of internal model control system. In this paper, all Laplace variables s have been omitted for simplicity. Where, G_P is transfer function of the plant to be controlled, and G_N is normal model of plant, i.e. the internal model of the plant in this system. Q is internal model controller. e and u represent the tracking error and actuating signal. r, d, n and y represent the reference input, the disturbance, observed noise and observed output, respectively. The internal model control structure shown in Fig.1can be transformed into a classical feedback controller structure shown in Fig.2. In Fig.2, H is feedback controller. The relationship between the Q and H is expressed as:

$$H = \frac{Q}{1 - QG_N} \ . \tag{1}$$

Refer to Fig. 1 and Fig. 2, we can get

$$\begin{aligned} Y &= \frac{G_P Q}{1+[G_P - G_N]Q} R + \frac{1 - G_N Q}{1+[G_P - G_N]Q} D - \frac{G_P Q}{1+[G_P - G_N]Q} N \\ &= \frac{HG_P}{1+HG_P} R + \frac{1}{1+HG_P} D - \frac{HG_P}{1+HG_P} N \\ &= G_{ry} R + G_{dy} D - G_{ny} N \end{aligned} \tag{2}$$

where G_{ry} represents the target tracking characteristics between the input r and the output y, G_{dy} and G_{ny} represent the feedback characteristics between the disturbance d and the output y, observed noise n and the output y, respectively.

Generally, the performance objectives of the feedback controller H can be summarized as follows:

- To enable the output y to track the input r following

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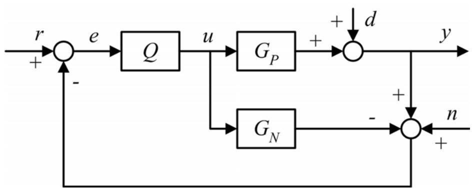

Fig.1 Internal model controller structure.

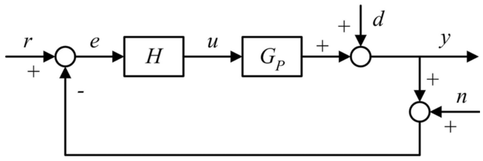

Fig. 2 Classical feedback controller structure.

some pre-specified functions.

- To minimize the effect of the disturbance d, the noise n and the plant uncertainty on the outputs y.

According to the system model shown in Fig. 2, the objective of the feedback controller H is to ensure that the error e remains small in spite of disturbances d and n. The tracking error e is given as:

$$
\begin{aligned}
E &= R - Y \\
&= (1+G_P H)^{-1} \cdot R - (1+G_P H)^{-1} \cdot D + (1+G_P H)^{-1} G_P H \cdot
\end{aligned} \tag{3}
$$

The control objective is to make $e \approx 0$, that is

$$E = 0 \cdot R - 0 \cdot D + 0 \cdot N \,. \tag{4}$$

The first two parts in (4) are referred to as disturbance rejection and command tracking and they can be achieved ideally by $H \approx \infty$. If the internal model is perfect, it is equivalent to the equation: $G_P = G_N$. In addition, if G_N and Q are stable, the feedback system with internal model control is stable. In this case, it is tempting to let $Q = G_N^{-1}$, the output of control system is achieved:

$$Y = 1 \cdot R + 0 \cdot D - 1 \cdot N \,. \tag{5}$$

However, the perfect control, $Q = G_N^{-1}$ is seldom possible and is difficult to accomplish. Therefore, the low pass filter F is integrated into controller, and let $Q = G_N^{-1} F$, where F denotes IMC filter expressed as follows:

$$F = \frac{1}{(1+\lambda_q s)^n} \,. \tag{6}$$

where λ_q is the time constant, and n is the order used to make proper Q.

In addition, the third part of (4) represents zero noise transmission. This requires that the feedback controller must be small in magnitude: $H \approx 0$.

The aforementioned requirements are conflicting. The cut-off frequency of the sensitivity function should not be set on higher region, and it is difficult to compromise for different frequencies on which has different performance for the disturbance rejection, reference command tracking and reduce the sensitivity to sensor noise and load parameters variations. In addition, if the model is not exact, the control performance is not perfect.

III. Machine model of PMLSM

In this paper, the permanent magnet linear synchronous motor (PMLSM) is used to position servo system. The d-q axes model can be used when only fundamental component is considered and is characterized as following:

The voltages equation

$$
\begin{cases}
u_d = R_s i_d + p\psi_d - \dfrac{\pi}{\tau} v \psi_q \\
u_q = R_s i_q + p\psi_q + \dfrac{\pi}{\tau} v \psi_d
\end{cases} \tag{7}
$$

where u_d, u_q are d, q axis mover voltage, R_s is mover resistance, i_d, i_q and ψ_d, ψ_q are the mover current and the mover flux linkage of d, q axis, respectively, τ is the pole pitch, v is the velocity of moving part and p is derivative operator.

The flux linkage equation

$$
\begin{cases}
\psi_d = L_d i_d + \psi_{PM} \\
\psi_q = L_q i_q
\end{cases} \tag{8}
$$

where L_d, L_q are mover inductance of d, q axis and ψ_{PM} is the stator permanent magnet flux linkage.

The electromagnet thrust is

$$F_e = \frac{3\pi}{2\tau} [\psi_{PM} i_q + (L_d - L_q) i_d i_q] \,. \tag{9}$$

where F_e is the output electromagnet thrust.

The motion equation

$$M \frac{dv}{dt} = F_e - F_L - Dv \,. \tag{10}$$

where M is the mass of moving part including the load, F_L is the load disturbance and D is the viscous friction coefficient.

When the field-oriented control strategy is applied for PMLSM drive, the current vector of mover is controlled to be orthogonal to the permanent magnet field of the stator. With the flux component current $i_d = 0$, the dynamic mode of the system can be simplified and the output electromagnet thrust is expressed as follows:

$$F_e = \frac{3\pi}{2\tau} \psi_{PM} i_q = K_f i_q \tag{11}$$

where K_f is thrust constant.

Fig. 3 shows the structure of the proposed two-degree-of-freedom fuzzy internal model control system. Here, K and B are the feedforward controller and the feedback controller, respectively. The target tracking characteristics are specified by K, the feedback characteristics for the disturbance and noise are specified by B. e_m, e and Δe represent the model

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error, tracking error and the change of the error e, respectively. The feedforward controller K is designed to satisfy the target tracking characteristics and is conventionally designed as:

$$K = G_{N\_}^{-1} F \tag{12}$$

where $G_{N\_}^{-1}$ is the component of the minimum phase of G_N. The feedback controller B is designed to minimize the norm $\|G_{dy}\|$ and $\|G_{ny}\|$ of the feedback characteristics. In this paper, the feedback controller is given as:

$$B = \frac{K_F}{1 + \lambda s} \tag{13}$$

where K_F is constant. For the IMC structure, if the model matches the plant inexactly, the performance of the disturbance rejection will be reduced. To overcome this problem in position servo system, the constant λ of feedback controller B should be adjusted according to fuzzy logic.

IV. Fuzzy Internal Model Control

Generally, the larger the parameter λ of the feedback filter is, the slower the dynamic responses and lower sensitivity to varying of the model parameters. In contrast, the smaller λ is, the more rapid dynamic response and weaker robustness, it is likely to oscillate [5], [6]. The adjusting method of λ can be summarized as: if the error is large, λ should be reduced to minimize the error and thereby the output tends toward reference rapidly. λ is in inverse proportion to the error. When the error is less, λ should be achieved larger to avoid overshoot and oscillation, at the same time, if the dynamic response is tending slowly toward setting value, i.e. the change of the error e is little, the parameter λ should be moderate value to avoid overshoot and improve performance of dynamic responses.

The membership functions related with variables e, Δe and λ are demonstrated in Table I and Table II, respectively. Where, the basic discussion universe of e, Δe and λ are determined as {-3,3}, {-3,3} and {0.1,0.5}, respectively.

Using aforementioned membership functions and adjustment strategy, the control rules are established and shown in Table III.

In the defuzzification step, the centroid formula is used to defuzzify the parameter λ adjusted on-line.

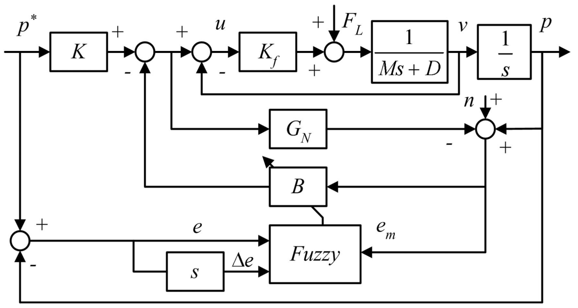

Fig. 3 Proposed two-degree-of-freedom fuzzy internal model control system

TABLE I
Fuzzy membership function of variable e and Δe

e, Δe	Grade						
	-3	-2	-1	0	1	2	3
NB	0	0	0	0	0	0.6	1
NM	0	0	0	0	0.6	1	0.6
NS	0	0	0	0.6	1	0.6	0
ZE	0	0	0.6	1	0.6	0	0
PS	0	0.6	1	0.6	0	0	0
PM	0.6	1	0.6	0	0	0	0
PB	1	0.6	0	0	0	0	0

TABLE II
Fuzzy membership function of variable λ

λ	Grade				
	0.1	0.2	0.3	0.4	0.5
VB	0	0	0	0.5	1
B	0	0	0.5	1	0.5
M	0	0.5	1	0.5	0
S	0.5	1	0.5	0	0
VS	1	0.5	0	0	0

TABLE III
Table Of Fuzzy Control Rules

e	Δe						
	NB	NM	NS	ZE	PS	PM	PB
NB	VS	VS	VS	VS	VS	VS	VS
NM	M	M	S	S	S	M	M
NS	B	B	M	M	M	B	B
ZE	VB	VB	B	M	B	VB	VB
PS	B	B	M	M	M	B	B
PM	M	M	S	S	S	M	M
PB	VS	VS	VS	VS	VS	VS	VS

V. Simulation Result and Analysis

MATLAB6.0 simulation software is used to simulate the strategy proposed in this paper. The parameters of the PMLSM servo system are: k_f = 25N·/A, D = 1.2N·s/m, M = 10kg. Fig.4 indicates the position response under the step function command. The step response under the step function disturbance (F_L=100N, t>0.8s) is shown in Fig5. The curve a in figures corresponds to the two-degree-of-freedom fuzzy internal model control and the curve b corresponds to the conventional PID control. The results show that the proposed control strategy has better position tracking performance and very stronger robustness to external disturbance than PID control.

VI. Conclusions

In this paper, we propose a two-degree-of-freedom internal model control method based on fuzzy logic, which adjust the parameter of feedback controller on-line for the PMLSM position servo system. It can be seen from the comparison of the simulated curves, the position tracking performance and the robustness to external disturbance based on fuzzy logic is obviously superior to traditional PID control. The control system structure is simplified and has fast dynamic response, while parameter identification is not demanded

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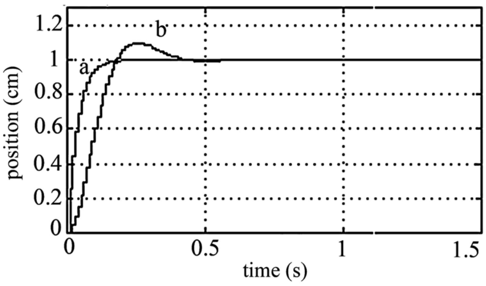

Fig. 4. Position respond curve.

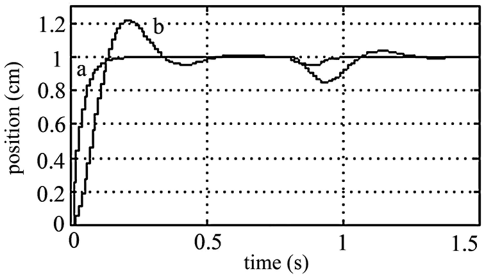

Fig. 5. Position respond curve under disturbance.

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