Application of Fuzzy Controller in the Speed Control of Permanent Magnet Linear Motors*

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Abstract: In this paper, a fuzzy controller is applied in the speed control of permanent magnet linear motors to promote their speed control performances. At the same time, the detailed design of the fuzzy controller is given. Fuzzy controllers can achieve high dynamic performance, but cannot achieve high static performance since fuzzy controllers have no integral part, especially when permanent magnet linear motors are influenced by strong force disturbances. The paper designs a disturbance observer to compensate the force disturbances based on the mathematical model of permanent magnet linear motors. So the influence of the force disturbance is eliminated, and the speed control effect of permanent magnet linear motors is increased. Simulation results show the fuzzy controller with the compensation of disturbance observer has a higher performance than the traditional PI. The experiment results also verify its higher dynamic and static performances in the speed control of permanent magnet linear motors.

Key Words: Fuzzy control, PMLM, speed control, disturbance observer

1 INTRODUCTION

Because of their advantages of high precision, high speed over rotation motors and other linear motors permanent magnetic linear motors(PMLMs) have many expected applications in various key semiconductor fabrications, robots and so on. PID controller has been widely used in the servo control system of PMLM. PID controller has its advantages such as simple structure, stable output and not to require precise mathematic model. But when system requires high dynamic control performance, PID controller cannot run very well and fuzzy controller is a good substitute. Fuzzy controller can convert the knowledge of experts into the fuzzy sets and intelligently tune the output of control system using fuzzy inference rules. This method also does not require precise mathematic model and has high robust performance. In recent years, fuzzy controller has been widely investigated and been applied in the control system of PMLMs[3-8].

But the control effect of fuzzy controller is reduced by the force disturbances since fuzzy controller has no integral part[9, 10]. In this paper, a disturbance observer is designed to compensate the force disturbances based on the built mathematic model of PMLMs. The results show the force disturbances are alleviated and the control performance of PMLMs are improved.

2 ANALYSIS OF CONTROL SYSTEM OF PMLMS

A PMLM is a multi-variable, nonlinear, strong-coupled system, and the predominant nonlinear effects are various frictional components(Coulomb, viscous, and striction) and force ripple arising from imperfections in the underlying components. Fig. 1 shows the force model of a PMLM, in which the sum of the force vectors must be zero so that the PMLM can run on a stable speed or stay at a position.

\[
\begin{align*}
\text{f}_{\text{load}} &+ f_{\text{rip}} + f_{\text{n}}(x) = \text{f}_{\text{applied}}(t) + f(t) \\
\end{align*}
\]

According to [1], the dynamics of a PMLM can be described by
\[
\begin{cases}
\dot{f}(t) = k_{f} i_{q}(t) \\
\dot{f}(t) = mv + Bv + f_{\text{load}}(t) + f_{\text{rip}}(x) + f_{n}(t)
\end{cases}
\]

Where \(v\) and \(i_{q}(t)\) are the time-varying motor terminal voltage and the equivalent armature current, respectively; \(x(t)\) is the motor position; \(k_{f}\) is the force coefficient related with flux linkage of a PMLM; \(m\) is the mass of a carriage; \(f(t)\) and \(f_{\text{load}}(t)\) are the developed force and the applied load force, respectively; and \(f_{\text{rip}}(x)\) denote the force ripple, \(f_{n}(t)\) denotes the other force disturbances.

Neglecting the nonlinearities in(2), and combining with(1), the following equation can be acquired
\[
i_{q} = \frac{m}{k_{f}}v + \frac{B}{k_{f}}v
\]

3 DESIGN OF FUZZY CONTROLLER

A fuzzy controller is used in the velocity circle of a PMLM substituting a traditional controller, which is show in Fig. 2. Where \(v'\) and \(i_{q}'\) are the expected velocity and expected torque current, respectively. The fuzzy controller includes four parts: fuzzifier, fuzzy inference, defuzzifier and fuzzy rules.

Speed error \(e\) and differential of speed error are set as the input of the fuzzy controller and tuned current \(U\) is the output. are set for 12 discourse regions, and they belong to 7 fuzzy sets, which are \{PB, PM, PS, ZO, NS, NM, NB\}.

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The fuzzy system sets 12 universes of discourse for the fuzzy variables \( e \), \( ec \) and \( U \), which are \((-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6)\), and these variables share seven fuzzy sets: PB, PM, PS, ZO, NS, NM and MB. The membership functions of these fuzzy sets for position are shown in Fig. 3. In Fig. 3 the large overlap between these universes of discourse ensures a smooth switch between different universes of discourse.

After fuzzifying the input and output variables, fuzzy rules are built based on the knowledge of experts and fuzzy inference is performed according to the rules. Using Mamdani method, 49 inference rules are generated since the input variable \( e \) and \( ec \) all have 7 fuzzy sets. The inference rules are shown in Table 1, and their inference processes are described as follows

**Rule1:** If \( e = NB \) and \( ec = NB \) then \( U = NB \)

**Rule2:** If \( e = NB \) and \( ec = NM \) then \( U = NB \)

**Rule49:** If \( e = PB \) and \( ec = PB \) then \( U = PB \)

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Fuzzy output is acquired by the fuzzy inference rules, but the fuzzy output must be defuzzified to generate the finally required output. With the center-average defuzzifier, we have

\[
y = \frac{\sum_{i=1}^{m} \mu_i' c_i'}{\sum_{i=1}^{m} \mu_i'}
\]

Where \( \mu_i' \) is the firing strength of the \( i \)-th rule and \( c_i' \) is the midpoint of the \( i \)-th rule output.

### 4 DESIGN OF DISTURBANCE OBSERVER

Though fuzzy controller has many advantages, fuzzy controller is essentially a class of nonlinear proportional and differential (PD) controller because it has no integral part[12]. So the force disturbances will generate the static control error of the system and the error is

\[
e_{sn} = - \frac{G_s N_s}{1 + G_s}(s)\]

Where \( e_{sn} \) is the static error generated by the force disturbances; \( N_s \) is the force disturbances; \( G_s(s) \) is the transfer function from torque current to velocity; \( G_i(s) \) is the open-loop transform function. If the transform function of fuzzy controller is \( G_f(s) \), \( G_f(s) \) is equal to \( G_f(s) \cdot G_s(s) \).

Equation 6 shows the static control error of the system increases with the increase of the force disturbances. So it is very important to suppress force disturbances especially when the force disturbances are big.

Equation 3 shows the transfer function from torque current to velocity is essentially of first order. The transfer function of PMLMs is

\[
G_s(s) = \frac{1}{k_f}\frac{m}{s^2 + B}\]

Because the disturbance observer incorporates the inverse of the plant[1], the compensation current of the disturbance observer can be calculated as follows

\[
\Delta i_1(t) = \frac{1}{k_f}[k_f \dot{q} \dot{q}(t) - (\dot{m}\ddot{x} + \ddot{B} \ddot{y})]
\]

Where \( \dot{m} \) and \( \ddot{B} \) are the estimated mass of a carriage and estimated viscous friction coefficient, respectively. At the same time a low-pass filter \( F \) is required so that the designed disturbance observer is proper and practically realizable. Because the transfer function from torque current to velocity is of first order, \( F \) is designed as a first-order filter.
Fig. 4 Architecture of the disturbance observer of PMLMs

\[
F(s) = \frac{1}{1 + \tau \cdot s}
\]  
(8)

Where \( \tau \) is the time constant. The designed disturbance observer is shown in Fig. 4.

5 SIMULATION AND EXPERIMENTAL RESULTS

Simulations and experiments are made for the speed control of a PMLM with the linear encoder whose resolution is 1 \( \mu \)m, and the experimental platform of the PMLM is shown in Fig. 5. The time constant \( \tau \) is set for 0.01 and the parameters of the PMLM are provided as follows:

\[
R = 1.25 \Omega, \quad L = 5.25 \text{ mH}, \quad m = 18 \text{ kg}, \quad f_k = 0.042 \text{ Wb}
\]

Fig. 5 Experimental platform of a PMLM

A PI controller is applied to compare the control effects of the fuzzy controller. Parameters of the PI controller are set for \( k_c = 1600 \), \( k_i = 420 \).

In the simulations, a load of 15 N is applied to the PMLM. Fig. 6 shows the simulation results of speed control. PIDC and FCO are the step responses of the PI controller and fuzzy controller with the compensation of disturbance observer. The results show that fuzzy controller with the compensation of disturbance observer has faster response speed, smaller overshoot and smaller fluctuation than PI controller.

Fig. 6 The step responses of PID controller fuzzy system with disturbance observer

Fig. 7 shows the experimental results of speed control of the PMLM. The expected speed is 0.2 m/s and the sampling time is 400\( \mu \)s. The results are printed in the environment of C language and the results further verify the fuzzy controller with the compensation of a disturbance observer can acquire more high dynamic and static performances than PI controller.
In the paper, fuzzy controller is applied to the speed control of PMLMs to promote their speed control performances. For the deficiency of integral controller in fuzzy controller, the paper designed a disturbance observer to compensate the force disturbances based on the mathematical model of PMLMs. Simulation and experimental results show the fuzzy controller with the compensation of disturbance observer can acquire both high dynamic and static performances in speed control of PMLMs.

REFERENCES