Adaptive-Fuzzy-Identification-Based Sliding-Mode Control for Linear Ultrasonic Motor

CHIH-MIN LIN ANG-BUNG TING MING-CHIA LI

*Department of Electrical Engineering, Yuan Ze University, Chung-Li, Tao-Yuan, 320, Taiwan, Republic of China, *E-mail: cml@saturn.yzu.edu.tw*

Abstract:- An adaptive-fuzzy-identification-based sliding-mode control (AFISMC) design method is proposed to control an Linear Ultrasonic Motor (LUSM). Since the dynamic characteristic of the LUSM is difficult to obtain and the motor parameters are time varying, the AFISMC system is derived to automatically adjust the fuzzy rules without using any plant model of the LUSM. In the proposed AFISMC design method, a fuzzy system is utilized to identify the unknown system dynamic function. In addition, an error estimation mechanism is investigated to estimate the bound of approximation error. The experimental results show that the proposed AFISMC design method can achieve favorable control performance for the LUSM.

Key-Words:- Fuzzy system, Adaptive law, Sliding-mode control, System identification, Lyapunov function, Linear ultrasonic motor

1 Introduction

Piezoelectric ceramic ultrasonic motors or ultrasonic motors (USM) are primarily piezoelectric ceramic actuators. USM has some merits such as smaller dimension, high holding force, silence, and more minimum step size than the class electromagnetic motors, etc. [1]. The driving principle of USM is based on the ultrasonic vibration force of piezoelectric ceramic elements and mechanical frictional force. Therefore, their mathematical model are complex [2], and the motor parameters are time varying because of increasing temperature and changes in motor drive operating conditions [3]. In additional, piezoelectric ceramic linear ultrasonic motor (LUSM) is one of the new kinds of USM. Without using any mechanical transmissions to realize the linear motion, the effect of system uncertainty is directly transmitted to the moving table of LUSM. Thus, a controller for LUSM, which can achieve required high-accuracy in spite of nonlinear uncertainty effects, is more difficult to be designed than for USM.

In the conventional control theory, mathematical tools based on the system models usually solve most of the control problem. But in the LUSM control systems, whose accurate mathematical models are not available; thus, the favorable control performance can not be still achieved.

Because a fuzzy system can provide a good approximation of an unknown function, it is an alternative to conventional control technique [4].

However, the huge amount of fuzzy rules required for a high-order system makes the analysis complex. To resolve this, some researchers have proposed the fuzzy control design methods based on the sliding-mode control scheme. These approaches are referred to as fuzzy sliding-mode controls [5]. However, the design of the rule bases for the fuzzy sliding-mode control still has relied on a priori knowledge. Obviously, it is difficult for human experts to examine all the input-output data from a complex system to find proper rules for the fuzzy system. To cope with this difficulty, several researchers have presented the adaptive fuzzy control design methods [6, 7]. The adaptive law of the adaptive fuzzy control, based on the Lyapunov synthesis approach, regulates the fuzzy rules automatically; thus the stability and the robustness of the system can be guaranteed.

The motivation of this paper is to develop an adaptive-fuzzy-identification-based sliding-mode control (AFISMC) for the LUSM. The AFISMC possesses the advantages that it can automatically adjust the fuzzy rules to identify the unknown system dynamics. The adaptive laws of the proposed AFISMC system is derived based on the Lyapunov function; thus the stability of the system can be guaranteed. Moreover, to relax the requirement for the bound of approximation error, an estimation algorithm is investigated to estimate the bound of approximation error. Finally, the experimental results are provided to illustrate the effectiveness of the proposed design method.

2 Piezoelectric Ceramic Linear Ultrasonic Motor

The structure of the LUSM is a large face of a relatively thin rectangular piezoelectric ceramic device. The movement of LUSM is constrained by four support springs with large stiffness. Because the mathematical model of LUSM is very complicated and the parameter of the elements are not easy to know. In the derivation of the model, the model is obtained to include most nonlinear effects like friction and force ripple. The general mathematical model of the system can be described by the following equations

$$[M + m(t)]\ddot{d}(t) = u(t) - f(\mathbf{d};t) \qquad (1)$$

where $\mathbf{d} = [d(t), \dot{d}(t), \ddot{d}(t)]$ represent the position, velocity and acceleration of the moving table, respectively; M is the mass of the moving table; $m(t)$ is the mass of the payload; $u(t)$ is the input force to LUSM; and $f(\mathbf{d};t)$ is the normalized lump force of the uncertain nonlinearities such as friction, ripple force and external disturbance. Rewriting (1), the model of the LUSM drive system is obtained as

$$\ddot{d}(t) = \frac{-f(\mathbf{d};t)}{M + m(t)} + \frac{1}{M + m(t)}u(t)$$

$$= F_p(\mathbf{d};t) + G_p(t)u(t) \qquad (2)$$

where $F_p(\mathbf{d};t)$ is a nonlinear dynamic function, and $G_p(t)$ is a control gain. Assume that the mass of the payload is considered as a system uncertainty and rewrite (2) as

$$\ddot{d}(t) = F_p(\mathbf{d};t) + [G + \Delta G(t)]u(t)$$

$$= F(\mathbf{d};t) + Gu(t) \qquad (3)$$

where $F(\mathbf{d};t)$ is the unknown lumped uncertain system dynamics and is defined as $F(\mathbf{d};t) = F_p(\mathbf{d};t) + \Delta G(t)u(t)$; and G is the nominal value of $G_p(t)$ and is defined as

$G = \frac{1}{M}$.

3 Fuzzy System Identifier

Assume that there are m rules in a fuzzy rule base and each of them has the following form:

Rule i : If x is $\tilde{A}_i$ Then y is $\tilde{B}_i$ (4)

where x is the input variables of the fuzzy system; y is the output variable of the fuzzy system; and $\tilde{A}_i$ and $\tilde{B}_i$ are the linguistic terms characterized by their corresponding fuzzy membership function $\mu_{\tilde{A}_i}(x)$ and $\mu_{\tilde{B}_i}(y)$, respectively. The defuzzification of the control output is accomplished by the method of center-of-gravity [6]

$$y = \sum_{i=1}^{m} w_i \times \theta_i / \sum_{i=1}^{m} w_i \qquad (5)$$

where w_i is the firing weight of the i-th rule and the singleton fuzzification of $\mu_{\tilde{B}_i}(y)$ is denoted by θ_i. If θ_i are chosen as adjustable parameters, (5) can be expressed in a vector form as

$$y = \boldsymbol{\theta}^T \boldsymbol{\xi} \qquad (6)$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, ..., \theta_m]^T$ is a parameter vector and $\boldsymbol{\xi} = [\xi_1, \xi_2, ..., \xi_m]^T$ is a regressive vector with ξ_i defined as

$$\xi_i = w_i / \sum_{i=1}^{m} w_i \qquad (7)$$

It has been proven that the fuzzy system in (6) is a universal approximator [6]. This implies that there exists an expansion of (6) such that it can uniformly approximate a nonlinear even time-varying function Θ. By the universal approximation theorem, there exists an ideal vector $\boldsymbol{\theta}^*$ such that

$$\Theta = \boldsymbol{\theta}^{*T} \boldsymbol{\xi} + \omega \qquad (8)$$

where ω is the approximation error, which generally decreases as the size m of fuzzy system increases. The optimal vector $\boldsymbol{\theta}^*$, that is needed to best approximate a given nonlinear function Θ, is difficult to determine. In fact, it may not even be unique. Then an estimate of Θ can be given by

$$\hat{\Theta} = \hat{\boldsymbol{\theta}}^T \boldsymbol{\xi} \qquad (9)$$

where $\hat{\boldsymbol{\theta}}$ is the estimated vector of the optimal vector $\boldsymbol{\theta}^*$, that are provided by some on-line weight tuning algorithms subsequently to be detailed.

4 Adaptive-Fuzzy-Identification-Based Sliding-Mode Control

The control objective is to find a control law so that the position of the moving table, $d(t)$, can track the desired position command, $d_c(t)$. To achieve the control objective, define a position tracking error as follow

$$e(t) = d(t) - d_r(t) \qquad (10)$$

where $d_r(t)$ is the position reference trajectory, which is specified by the position command followed by a reference model. Assume that the parameters of the LUSM in (3) are well known, an ideal controller can be obtained as

$$u^*(t) = G^{-1}\left[- F(\mathbf{d};t) + \ddot{d}_r(t) - k_1 \dot{e}(t) - k_2 e(t)\right] \qquad (11)$$

Applying (11) into (3) results in

$$\ddot{e}(t) + k_1 \dot{e}(t) + k_2 e(t) = 0 \qquad (12)$$

If k_1 and k_2 are chosen to correspond to the coefficients of a Hurwitz polynomial, that is a polynomial whose roots lie strictly in the open left half of the complex plane, then it implies that $\lim_{t\to\infty} e(t) = 0$. Since the lumped uncertain system dynamics $F(\mathbf{d};t)$ is unknown, the ideal controller can not be implemented. In this study, a fuzzy system identifier, based on the approximation theorem, will be utilized to identify this unknown system dynamics.

A fuzzy-identification sliding-mode control for linear ultrasonic motor drive system is proposed, where the sliding surface $r(t)$ is defined as

$$r(t) = \dot{e}(t) + k_1\, e(t) + k_2 \int_0^t e(\tau)d\tau \qquad (13)$$

By the universal approximation theorem, there exists an optimal fuzzy system F^* in the form of (6) such that [6]

$$F = F^* + \omega = \boldsymbol{\theta}^{*T}\boldsymbol{\xi} + \omega \qquad (14)$$

where ω is the approximation error and is assumed to be bounded by $|\omega| \le \Delta$. An uncertainty observer is defined as

$$\hat{F} = \hat{\boldsymbol{\theta}}^T \boldsymbol{\xi} \qquad (15)$$

where $\hat{\boldsymbol{\theta}}$ is the estimated vector of $\boldsymbol{\theta}^*$. The control law for the AFISMC is assumed to take the following form:

$$u = u_{mc} + u_{hc} \qquad (16)$$

where u_{mc} is the main controller and u_{hc} is the hitting controller with chosen as

$$u_{mc} = G^{-1}[-\hat{F} + \ddot{d}_r(t) - k_1\dot{e}(t) - k_2 e(t)] \qquad (17)$$

$$u_{hc} = -G^{-1}\hat{\Delta}\,\mathrm{sgn}(r(t)) \qquad (18)$$

where $\hat{\Delta}$ is the estimated bound value of Δ and $\mathrm{sgn}(\cdot)$ is a sign function. By substituting (16) into (3), it is revealed that

$$\ddot{e}(t) + k_1\, \dot{e}(t) + k_2\, e(t) = F - \hat{F} - \hat{\Delta}\,\mathrm{sgn}(r(t)) = \dot{r}(t) \qquad (19)$$

Define the estimated error $\tilde{F}$ as

$$\tilde{F} = F - \hat{F} = \boldsymbol{\theta}^{*T}\boldsymbol{\xi} - \hat{\boldsymbol{\theta}}^T\boldsymbol{\xi} + \omega \qquad (20)$$

For simplicity of discussion, define $\boldsymbol{\varphi} = \boldsymbol{\theta}^* - \hat{\boldsymbol{\theta}}$ to obtain a rewritten form of (20) as

$$\tilde{F} = \boldsymbol{\varphi}^T \boldsymbol{\xi} + \omega \qquad (21)$$

Furthermore, consider a Lyapunov function candidate in the following form

$$V(r(t),\boldsymbol{\varphi},\tilde{\Delta}) = \frac{r^2(t)}{2} + \frac{\boldsymbol{\varphi}^T\boldsymbol{\varphi}}{2\eta_1} + \frac{\tilde{\Delta}^2}{2\eta_2} \qquad (22)$$

where η_1 and η_2 are positive constants and $\tilde{\Delta} = \Delta - \hat{\Delta}$ is the bound estimation error. Differentiating (22) with respect to time and using (19) and (20), it can obtain that

$$\dot{V}(r(t),\boldsymbol{\varphi},\tilde{\Delta}) = r(t)\dot{r}(t) + \boldsymbol{\varphi}^T\dot{\boldsymbol{\varphi}}/\eta_1 + \tilde{\Delta}\dot{\tilde{\Delta}}/\eta_2$$

$$= \boldsymbol{\varphi}^T(r(t)\boldsymbol{\xi} + \dot{\boldsymbol{\varphi}}/\eta_1) + r(t)\omega - |r(t)|\hat{\Delta} + \tilde{\Delta}\dot{\tilde{\Delta}}/\eta_2 \qquad (23)$$

If the adaptation laws are chosen as

$$\dot{\hat{\boldsymbol{\theta}}} = -\dot{\boldsymbol{\varphi}} = \eta_1 r(t)\boldsymbol{\xi} \qquad (24)$$

$$\dot{\hat{\Delta}} = -\dot{\tilde{\Delta}} = \eta_2 |r(t)| \qquad (25)$$

then (23) can be rewritten as

$$\dot{V}(r(t),\boldsymbol{\varphi},\tilde{\Delta})) = r(t)\omega - |r(t)|\Delta$$

$$\le |r(t)||\omega| - |r(t)|\Delta = -(\Delta - |\omega|)|r(t)| \le 0 \qquad (26)$$

By the adaptive laws, the AFISMC system can be guaranteed to be stable in the Lyapunov sense.

5 Experimental Results

To test the proposed control systems with high-accuracy motion control of the LUSM, two test conditions are provided in the experimentation, which are the nominal condition and the payload condition. The payload condition is the addition of one iron disk with 3.7 *kg* weight to the mass of the moving table. The control objective is to control the moving table to move 5*cm* periodically for a periodic step command. A second-order transfer function is chosen as the reference model for a periodic step command:

$$\frac{111.634}{s^2 + 2.11s + 111.634} \qquad (27)$$

The parameters of the proposed control system are selected as follows:

$$k_1 = 2,\ k_2 = 1,\ \eta_1 = 100,\ \eta_2 = 1 \qquad (28)$$

All the parameters are chosen through some trials to achieve favorable transient control performance in experimental considering the requirement of stability. The experimental results of the AFISMC system are shown in Fig. 2. The tracking responses are depicted in Figs. 2(a) and 2(c); and the associated control efforts are depicted in Figs. 2(b) and 2(d), respectively. From the experimental results, the high-accuracy motion tracking responses can be obtained under the nominal condition and the payload condition.

6 Conclusions

An adaptive-fuzzy-identification-based sliding-mode control (AFISMC) system is proposed to control a linear ultrasonic motor (LUSM). The adaptive laws based on the Lyapunov stability theorem can automatically adjust the parameter vector of the fuzzy system; thus the stability of the system can be guaranteed. From the experimental results, the high-speed high-accuracy control performance of the LUSM can be achieved.

Acknowledgment

This paper is supported by the National Science Council of the Republic of China under grant NSC 96-2218-E-216-001.

Reference

[1] T. Sashida, and T. Kenjo, *An Introduction to Ultrasonic Motors*, Clarendon Press, Oxford, 1993.

[2] N. W. Hagood, and A. J. Mefarland, “Modeling of A Piezoelectric Rotary Ultrasonic Motor,” *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, Vol. 42, No. 2, 1995, pp. 210-224.

[3] F. J. Lin, R. Y. Duan, and J. C. Yu, “An Ultrasonic Motor Drive Using A Current-Source Parallel-Resonant Inverter With Energy Feedback,” *IEEE Trans. Power Electron.*, Vol. 14, No. 1, 1999, pp. 31-42,.

[4] J. Yeh, and R. Langari, *Fuzzy Logic-Intelligence, Control and Information*, Prentice-Hall, Englewood Cliffs, New Jersey, 1999.

[5] B. J. Choi, S. W. Kwak, and B. K. Kim, “Design and Stability Analysis of Single-Input Fuzzy Logic Controller,” *IEEE Trans. Syst., Man, Cybern.,*, Vol. 30, No. 2, 2000, pp. 303-309.

[6] L. X. Wang, *Adaptive Fuzzy Systems and Control: Design and Stability Analysis*, Prentice-Hall, Englewood Cliffs, New Jersey, 1994.

[7] T. J. Koo, “Stable Model Reference Adaptive Fuzzy Control of a Class of Nonlinear Systems,” *IEEE Trans. Fuzzy Syst.*, Vol. 9, No. 4, 2001, pp. 624-636.

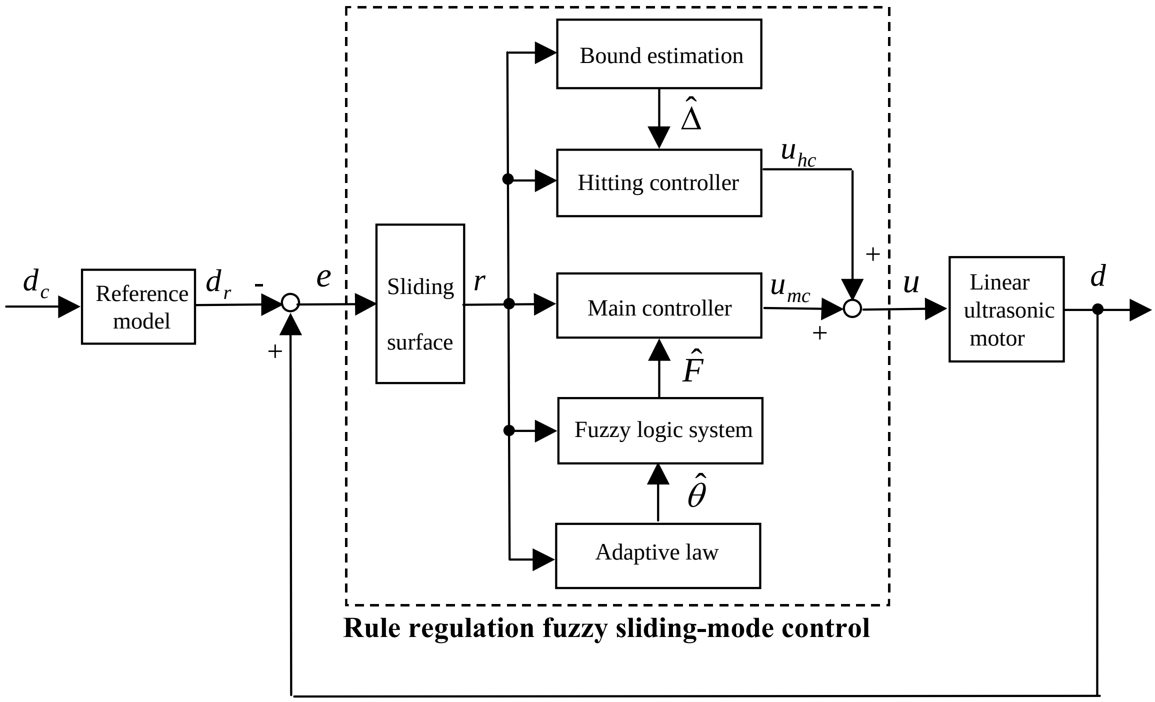

Figure 1 - The block diagram of the adaptive-fuzzy-identification-based sliding-mode control for linear ultrasonic motor system

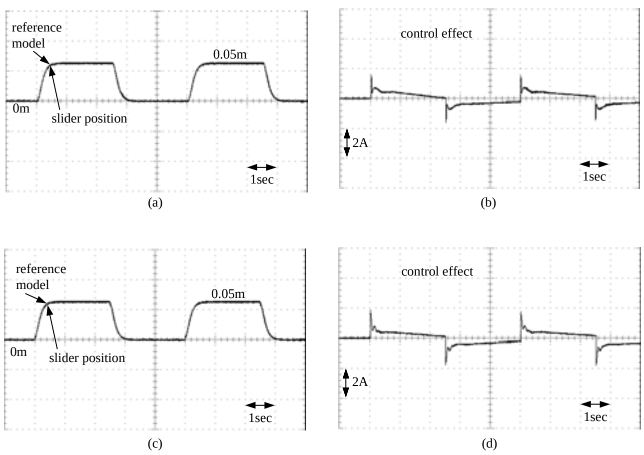

Figure 2 - Experimental results of AFISMC LUSM system due to a step command:
(a),(b) nominal condition; (c),(d) payload condition