Optimized Adaptive Sliding-mode Position Control System for Linear Induction Motor Drive

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Abstract—**This paper proposes an optimized adaptive position control system applied for a linear induction motor (LIM) drive taking into account the longitudinal end effects and uncertainties including the friction force. The dynamic mathematical model of an indirect field-oriented LIM drive is firstly derived for controlling the LIM. On the basis of a backstepping control law, a sliding mode controller (SMC) with embedded fuzzy boundary layer is designed to compensate the lumped uncertainties during the tracking control of periodic reference trajectories. Since it is difficult to obtain the bound of lumped uncertainties in advance in practical applications, an adaptive tuner based on the sense of Lyapunov stability theorem is derived to adjust the fuzzy boundary parameters in real-time. It is a quite complicated process of parameter tuning, especially for the proposed controller, due to the difficulty arisen from lacking of the accurate mathematical model of a system accompanied with unknown disturbance. Therefore, the soft-computing technique is adopted for off-line optimizing the controller parameters. The effectiveness of the proposed control scheme is validated through simulations and experiments for several scenarios. Finally, the advantages of performance improvement and robustness are illustrated at the end of the optimization procedure.**

Keywords—backstepping control; adaptive control; soft-computing optimization; position tracking; linear induction motors(LIM)

I. INTRODUCTION

The linear induction motors (LIM) yield the performance in satisfactory due to the merits such as high starting thrust force, simple structure replacement of the gear between motor and motion devices, reduction of mechanical losses, and easy maintenance, repairing and replacement [1-3]. From the aforementioned features, the LIM are widely used in the industrial applications, including automation, conveyer systems, transportation systems, actuators, material handling, elevators, and sliding door closers, CNC machine, robotic arm systems [4]. An accurate equivalent circuit model is essentially required to achieve high performance control for LIM. Most of the existing models of a LIM depend on field theory [5], and some studies [6, 7] used the RIM model to control LIM. However, they are not valid in high speed operation of LIM because of the end effects.

To deal with such uncertainties, many studies have been done in recent years to apply various approaches in the control field. Sliding mode control (SMC) is one of the powerful approaches to control nonlinear and uncertain systems [8, 9]. Fuzzy systems have supplanted conventional technologies in many applications, especially in control systems. One major feature of fuzzy logic is its ability to express the amount of ambiguity in human thinking. Nowadays, many researchers have tended to combine with fuzzy logic and SMC. The main advantage of fuzzy logic controller design based on SMC is that the fuzzy rules can be reduced, and the requirement of the uncertainty bound can be released. Wong et al. [10, 11] combined a fuzzy controller to remedy the chattering phenomena. However, the parameters of membership functions cannot be adjusted to afford optimal control efforts under the increasing system uncertainties.

In this paper, an indirect field-oriented control scheme for position tracking control of LIM is proposed. The combination of SMC and fuzzy logic control is used to obtain the robust tracking controller without control chattering inherent in conventional SMC. Based on Lyapunov stability theorem, an adaptive mechanism is derived to on-line adjust the fuzzy boundary parameter to confront the increasing external disturbances. Besides, to improve an accepted level of LIM position tracking performance in response to disturbances and uncertainties, a soft-computing optimization is applied. Since the electric drive controller is a complex problem due to the nonlinearities of the machines, power converter and controller, an adaptive neuro-fuzzy inference system (ANFIS) with Sugeno-type fuzzy model [12] is adapted to obtain the complex interdependencies of the controlled system. Subsequently, when considering a global optimum for multiple considerations, Genetics algorithm (GA) is employed to find the optimal controller parameters offline from the final winner of the genetic game [13-15]. In this way, the optimized controller can maintain normalcy in a desired level of position tracking. The simulated and the experimental results are provided to demonstrate the effectiveness of the proposed control system.

II. MODELING OF LIM CONSIDERING END EFFECTS

The equivalent voltage equations describing the linear induction motor can be described as [16, 17]:

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$$V_{ds} = R_s i_{ds} + p\lambda_{ds} - \frac{\pi n_p}{h} v_e \lambda_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \frac{\pi n_p}{h} v_e \lambda_{ds} \quad (2)$$

$$V_{dr} = R_r i_{dr} + p\lambda_{dr} - (\frac{\pi n_p}{h} v_e - \frac{\pi n_p}{h} v)\lambda_{qr} \quad (3)$$

$$V_{qr} = R_r i_{qr} + p\lambda_{qr} + (\frac{\pi n_p}{h} v_e - \frac{\pi n_p}{h} v)\lambda_{dr} \quad (4)$$

and the d/q-axis flux linkages of the primary and secondary are expressed as

$$\lambda_{ds} = L_{ls} i_{ds} + L_m \left[1 - f(Q)\right](i_{ds} + i_{dr}) \quad (5)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m \left[1 - f(Q)\right](i_{qs} + i_{qr}) \quad (6)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m \left[1 - f(Q)\right](i_{ds} + i_{dr}) \quad (7)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m \left[1 - f(Q)\right](i_{qs} + i_{qr}) \quad (8)$$

where subscripts "*s*" and "*r*" denote the primary and the secondary values;

$$f(Q) = \left(1 - e^{-Q}\right)\Big/ Q \quad (9)$$

$$Q = (l/v)/(L_r/R_r) \quad (10)$$

The electromagnetic thrust force is given by

$$F_e = K_f(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) = M\dot{v}_e + Dv_e + F_l \quad (11)$$

The other variables in (1)-(11) are defined as follows:

i_d, i_q	d-axis and q-axis current, respectively
v_e	synchronous linear velocity
v	mover linear velocity
R_r (R_s)	primary (secondary) resistance
L_r (L_s)	primary (secondary) inductance
L_{lr} (L_{ls})	primary (secondary) leakage inductance
L_m	mutual inductance
l	primary length in meters
K_f	force constant
F_l	external force disturbance
M	primary mass
D	viscous friction
h	pole pitch
p	differential operator (d/dt)

By assuming that the reference frame is aligned to the secondary flux, the following expressions are reasonably resulted

$$\lambda_{qr} = \dot{\lambda}_{qr} = 0\,, V_{dr} = V_{qr} = 0 \quad (12)$$

Moreover, by taking (3), (7) and (12), we can further derive the following flux linkage

$$\lambda_{dr} = \frac{L_m\left[1 - f(Q)\right]}{1 + [T_r - L_m f(Q)/R_r]p} i_{ds} \quad (13)$$

where $T_r = L_r/R_r$. The slip velocity signal can be obtained from (4)

$$v_{sl} = \frac{L_m}{T_r \lambda_{dr}} i_{qs} \quad (14)$$

Therefore, the system motor thrust force factor K_F can be summarized as a dynamic factor which is directly concerned with the motor speed.

$$F_e = K_F i_{qs}^* \quad (15)$$

$$H_p(s) = \frac{1}{Ms + D} \quad (16)$$

$$K_F = \frac{3n_p\pi\left\{L_m\left[1 - f(Q)\right]\right\}^2}{2h\left[L_r - L_m f(Q)\right]} i_{ds} \quad (17)$$

Note that here s denotes the Laplace operator. Now, a mechanical dynamic LIM driver system considering parameter variations, longitudinal end-effect, and external load disturbance can be expressed as shown below.

$$\dot{d} = x \quad (18)$$

$$\dot{x} = (\bar{A}_m + \Delta A)x + (\bar{B}_m + \Delta B)u + C(F_l + f(v)) \quad (19)$$

$$y = d \quad (20)$$

where d and x represent the mover position and velocity, respectively. Both $\bar{A}_m = -M/D$ and $\bar{B}_m = K_f/M$ are nominal condition parameters; ΔA and ΔB denote the uncertainties of system parameters arisen from M and D; $u = i_{qs}$ is the control input to the motor drive system; $f(v)$ denotes the friction forces. (19) can be written as

$$\dot{x} = \bar{A}_m x + \bar{B}_m u + F_d \quad (21)$$

where F_d is the system lumped uncertainties and defined as

$$F_d \equiv \Delta A x + \Delta B u + C(F_L + f(v)) \quad (22)$$

Here, by the fact that the sampling period of a digital processing estimator in practice is shorter in comparing with the variation of the system lumped uncertainties. Hence, such lumped uncertainties can be assumed to be bounded, that is,

$$\left|F_d(t)\right| \le \eta \quad (23)$$

where η is a given positive constant.

III. Control Design

To design a position tracking controller, it is reasonable to assume that the reference trajectory d^* and its first two derivatives $\dot{d}^*$ and $\ddot{d}^*$ are all bounded function with respect to time. For the objective of position tracking, define the tracking error and take its time derivative as follows:

$$e_y = y - y^* \tag{24}$$

$$\dot{e}_y = \dot{y} - \dot{y}^* \tag{25}$$

The sliding surface is defined as

$$s = ke_y + \dot{e}_y \tag{26}$$

In this paper, our control design is detailed in the following.

A. Sliding Mode Control with Fuzzy Boudary Layer

We take the sliding mode theorem and the backstepping derivation process based on Lyapunov theorem to find the basic structure of the adaptive controller. The lumped uncertainty is assumed to be bounded, that is, $|F_d| < \eta \bar{B}_m$, and then choose the Lyapunov candidate as

$$V_1 = \frac{1}{2} e_y^2 \tag{27}$$

The time derivative of V_1 is

$$\dot{V}_1 = e_y \dot{e}_y = e_y(s - ke_y) = e_y s - ke_y^2 \tag{28}$$

Next, let the Lyapunov function candidate be defined as

$$V_2 = V_1 + \frac{1}{2} s^2 \tag{29}$$

The time derivative of V_2 is

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + s\dot{s} \\ &= e_y s - ke_y^2 + s[-k\dot{e}_y + A_m(s + \dot{y}^* - ke_y) + \bar{B}_m u + F_d - \ddot{y}^*]\end{aligned} \tag{30}$$

The sliding mode control law can be formulate as

$$\begin{aligned}u_{SMC} &= u_{eq} + u_{sw} \\ &= \bar{B}_m^{-1}[-e_y - k\dot{e}_y - \bar{A}_m(s + \dot{y}^* - ke_y) + \ddot{y}^* - \gamma s - \eta \operatorname{sgn}(s)]\end{aligned} \tag{31}$$

where γ is a positive number.

In order to remedy the chattering phenomenon, the concept of fuzzy boundary is introduced to SMC design. The second step is to alternative the switch term $\eta \operatorname{sgn}(s)$ in (31). Let the sliding surface be the input linguistic variable of the fuzzy logic, and the control effort u_f be the output linguistic variable. The membership function can be depicted in Fig. 1.

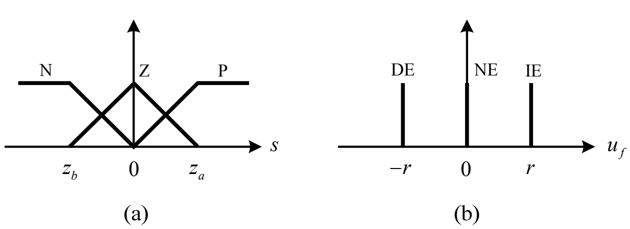

Fig. 1. The (a) input and (b) output membership function.

Now, the control effort can be expressed as shown below.

$$u_f = -r(\omega_1 - \omega_3) \tag{32}$$

where ω_1, ω_2, and ω_3 represent the weighting of each rule. As the motor moves faster, the system disturbance is more induced such as friction force and the end effects. Hence, the bound of lumped uncertainties could not be found readily in practical applications.

B. Adaptive Tunning Mechnism

We can find an optimal fuzzy boundary r^* to minimize the control efforts which also satisfies the sliding condition.

$$r^* = \frac{|F_d|}{|\omega_1 - \omega_3| \bar{B}_m} + \varepsilon \tag{33}$$

where ε is a small positive constant. In order to estimate the optimal value of the fuzzy boundary, the estimated error is defined as

$$\tilde{r} = \hat{r} - r^* \tag{34}$$

After we summarize the above part, the AFSMC law can finally be designed as

$$u_{AFSMC}(t) = u_{eq} + u_{af} = u_{eq} - \hat{r}(\omega_1 - \omega_3) \tag{35}$$

Now, we are going to derive the updating law for the fuzzy boundary layer. Based on the control law (34) with the estimated error (33), we choose a Lyapunov candidate as

$$V_3 = V_2 + \frac{1}{2}\frac{1}{\rho} \bar{B}_m \tilde{r}^2 \tag{36}$$

where ρ is an arbitrary positive constant. The time derivative of V_3 is

$$\dot{V}_3 = \dot{V}_2 + \frac{1}{\rho} \bar{B}_m \tilde{r}\dot{\hat{r}} \tag{37}$$

Then, we can extend (37) by using (34) and (35) to yield the following results:

$$\begin{aligned}\dot{V}_3 &= e_y s - ke_y^2 + s[k\dot{e}_y + A_m(s + \dot{y}^* - ke_y) + \bar{B}_m u \\ &\quad + F_d - \ddot{y}^*] + \frac{1}{\rho}\bar{B}_m \tilde{r}\dot{\hat{r}} \\ &\le -ke_y^2 - \gamma s^2 - s(\omega_1 - \omega_3)\bar{B}_m \varepsilon - s\bar{B}_m(\omega_1 - \omega_3)\tilde{r} + \frac{1}{\rho}\bar{B}_m \tilde{r}\dot{\hat{r}} \\ &= -ke_y^2 - \gamma s^2 - s(\omega_1 - \omega_3)\bar{B}_m \varepsilon + \frac{1}{\rho}\bar{B}_m \tilde{r}\left[\dot{\hat{r}} - \rho s(\omega_1 - \omega_3)\right]\end{aligned}$$

If the updating law for $\hat{r}$ is chosen as

$$\dot{\hat{r}} = \rho s(\omega_1 - \omega_3) \tag{38}$$

then $\dot{V}_3(t) \le 0$ according to the inequality $s(t)(\omega_1 - \omega_3) \ge 0$. Let function $W_3(t)$ be shown as below:

$$W_3(t) = ke_y^2 + \gamma s^2 + s(\omega_1 - \omega_3)\bar{B}_m \varepsilon \le -\dot{V}_3(t) \tag{39}$$

and integrate the function $W_3(t)$ with respect time

$$\int_0^t W_3(\tau)d\tau \le -\int_0^t \dot{V}_3(\tau)d\tau = V_3(0) - V_3(t) \tag{40}$$

Since $V_3(0)$ is bounded and $V_3(t)$ is nonincreasing and bounded, the following result can be obtained:

$$\lim_{t\to\infty}\int_0^t W_3(\tau)d\tau < \infty \tag{41}$$

Moreover, the function $\dot{W}_3(t)$ is bounded, and the function $W_3(t)$ is uniformly continuous. By applying Barbalat lemma [18], we have $\lim_{t\to\infty} W_3(t) = 0$. In the other words, the error state will converge to zero as time goes to infinity. Now that, the proposed controller can assure the system stability, asymptotic output tracking, and robust control performance.

C. Control Optimization Development

The proposed adaptive fuzzy sliding mode control (AFSMC) system is derived based on the sense of Lyapunov theorem, and the stability of the control system can be guaranteed. The system performance is sensitive to the controller's parameters. For instance, considering a large value of sliding surface slope *k*, the system will perform a fast response in application. However, the system may become unstable because of the high gain effort. Conversely, small value of *k* certainly makes the system more stable but the performance of the system may be degraded due to small values of the control signal. Here, the controller gains in (31) corresponding to our proposed control system, i.e., k and γ, are set as a data pair for the goal of optimization.

A system model is required for tuning the values of the controller gain. In some applications, the mathematical model cannot stand for the system characteristic exactly because of neglecting the variation of some parameters. Therefore, an adaptive neural-fuzzy architecture is embraced in this study to pursuit a better performance of the system controller. The ANFIS model is defined as two inputs and one output, and each input is corresponding to three fuzzy memberships. Once the ANFIS is setup, the next step is using this model with genetic algorithm to find the optimal system parameters.

TABLE. I. THE PARAMETERS OF GA USED IN THE APPLICATION.

Chromosome length	30 bits
Number of generations	100
Selection scheme	Tournament selection, Elitism
Crossover operator	Double point crossover
Crossover probability	0.85
Mutation probability	0.01
Termination criterion	100 generations

The definition of output of the approached system model is concerning with applying in GA procedure; on the other word, the output value of the ANFIS model is same as the fitness value used in GA application. Since the system control gains are matter of the system response like maximum overshoot and setting time, the fitness function should be defined considering such factors. The fitness function is defined as

$$f = \frac{1}{M_o + 2T_s + 1} \tag{42}$$

where M_o is the value of the maximum overshoot in meter per second and the T_s represents the settling time in millisecond. In this study, the conventional genetic algorithm is used and the parameter of GA is listed in Table I.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The proposed control system is initially simulated in Matlab package software, and in the meantime, the proposed controllers are carried out on the LIM plant. The LIM parameters for our plant are listed as follows:

i_{ds} = 2.42 A, R_s = 6.2689 Ω, R_r = 3.784 Ω, h = 0.027 m

L_m = 0.0825 H, L_s = L_r = 0.1021 H,

K_F = 55.8471 N/A, M = 3.25kg= 4.4245 Ns/V,

D = 40.95 kg/s= 65.52 N/V

Note that K_F is the nominal condition thrust coefficient without considering the primary end effect, and $\bar{M}$ and $\bar{D}$ denote the nominal values of system. In the simulation process, the performance of our proposed controller is compared with SMC in (31) and fuzzy sliding mode controller (FSMC) (32). Moreover, the proposed controller is also implemented on the plant to demonstrate the performance of our designed controller.

The friction forces and external load are considered as shown: F_l = 50sin(t); at $t \geqq 5$ *s*, increase the tracking frequency from 1 Hz to 3 Hz. The parameters' gains of the three controllers are chosen as $k=20,\ \gamma=10,\ \eta=10,\ r=10,\ \rho=650$. The simulation results of the three control system for tracking the periodic sinusoidal command are depicted in Fig. 2, and the associated control efforts are shown in Fig. 3. All three control systems perform well tracking response during 1-5 s. As the tracking commend increasing, the primary end effect induces time-varying external disturbances and, in this case, only the AFSMC system performs the robustness in the tracking response owning to the on-line adaptation capability. In addition, the control effort of AFSMC performs smooth response.

In the experiment, the hardware device includes a LIM, a motor drive unit, a real-time embedded control board, and a PC. The control signals are transmitted by a motor drive unit, which is manufactured by Servtronix Motion Control Ltd., to the LIM. The typical architecture of the motor drive unit incorporates a PWM inverter with a frequency of 16 kHz, an encoder inter face with digital filter and a quadruple frequency circuit. Also, the feedback signals such like a/b signals are sent over through the motor drive unit back to the embedded control board. The controller is realized in a real-time embedded control board for indirect field-oriented LIM drive system using the current-controlled technique. The designed controller operates in the real-time environment. The control interval of the position control loop is set at 10 ms. The data acquire chassis embedded D/A converter and encoder can provided motor information. The position is measured by a linear encoder with precision 1μm per pulse, and the D/A converter can feed the control signal to the servo drive card in advance to control the motor. The experimental setup is shown in Fig. 4.

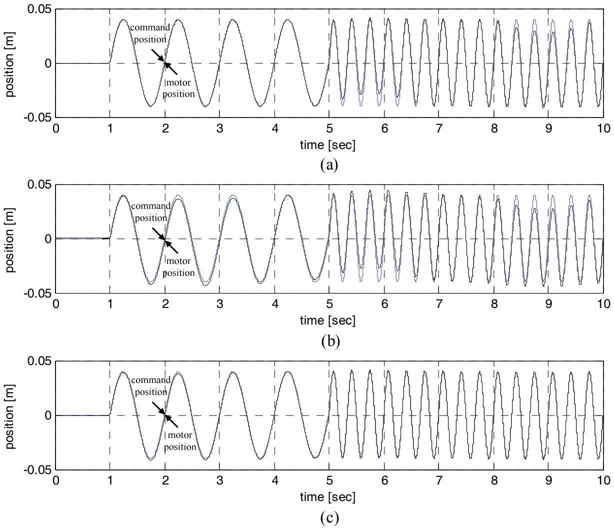

Fig. 2. Position tracking response (sinusoid). (a) SMC. (b) FSMC. (c) AFSMC.

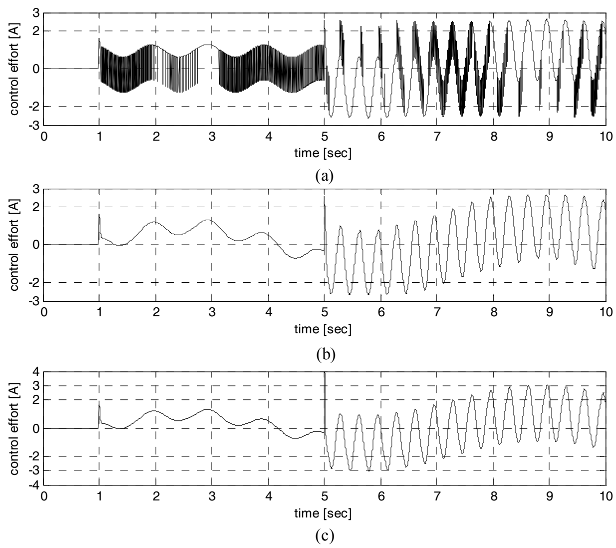

Fig. 3. Position tracking response (sinusoid). (a) SMC. (b) FSMC. (c) AFSMC.

Initially, the control parameters are chosen the same as that in the simulation phase. The tracking trajectory is a sinusoid command signal in frequency 1 Hz and 3Hz, and the amplitude is 0.04 m. From Figs. 5 and 6, the motor system can be influenced by some system disturbances such like end effects, friction force, or parameter variation, and cause the tracking efficiency decrease. The AFSMC system can perform well trajectory tracking in a limit time. By the work of the parameters optimization, one can realize the performance between original setting and the system parameters throughout optimization. We can find out the data pair (k, γ) with parameter optimization is convergence to the value which is (32.8782, 9.7656), and hence the new gains are chosen as $k=33,\ \gamma=10,\ \eta=10,\ r=10,\ \rho=20$. In Fig. 7, during the time to 2 sec, the original and optimization pattern both can track in accuracy to the reference signal. After 2 sec, the difference exists between the two sets of the controller parameters. The

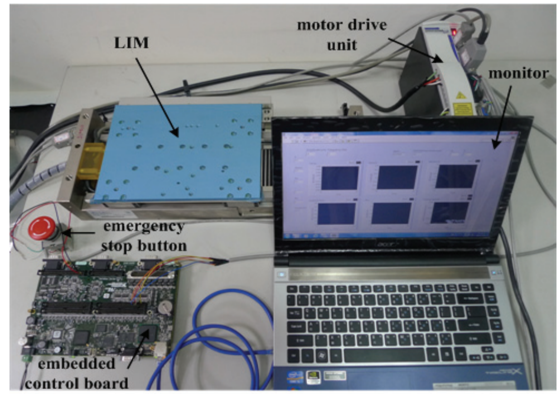

Fig. 4. The hardware devices for experiments.

optimized controller parameter sets can perform in a rapid transient response. The starting adaptive mechanism can immediately tune the fuzzy boundary in duration time to make sure the controller can achieve effective position tracking.

V. Conclusion

The design methodology of adaptive sliding mode with a fuzzy boundary layer has been presented. The dynamic drive model based on an indirect field-oriented control scheme of LIM considering the primary end effect is introduced. Moreover, the controller is derived based on the sense of Lyapunov stability theorem to adjust the controller parameters in real-time, and also for further confronting the increasing disturbance and uncertainties. The system parameters through the GA procedure perform well in position tracking than those gains in arbitrary selecting. Sinusoidal commands tracking in the numerical simulation and experimental results depicts the effectiveness of the proposed system. Moreover, additional experiments with various kinds of disturbance will be conducted to verify the robust performance of our system.

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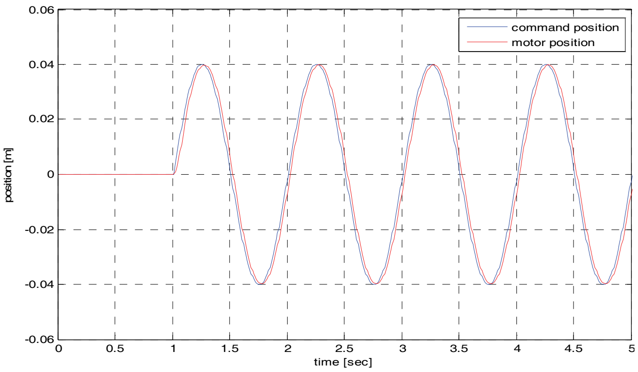
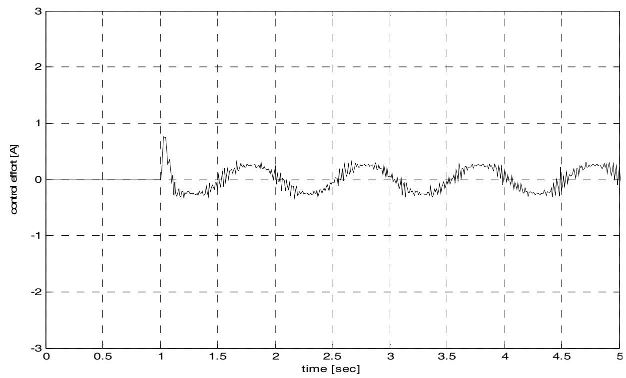
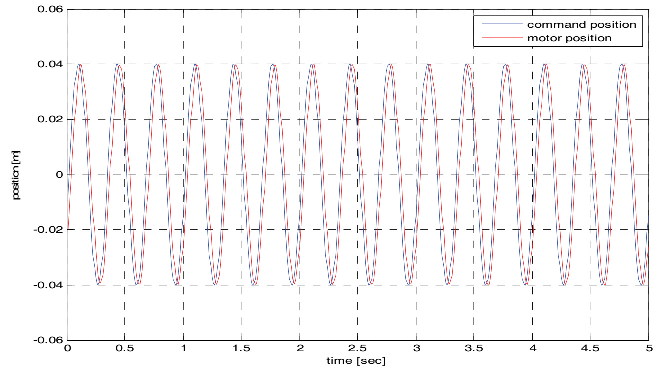


(a)

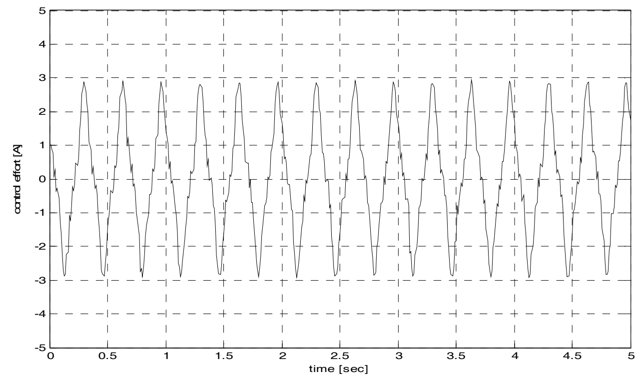


(b)

Fig. 5. Experimental results of AFSMC system in 1 Hz command signal. (a) Tracking response. (b) Control effort.



(a)



(b)

Fig. 6. Experimental results of AFSMC system in 3 Hz command signal. (a) Tracking response. (b) Control effort.

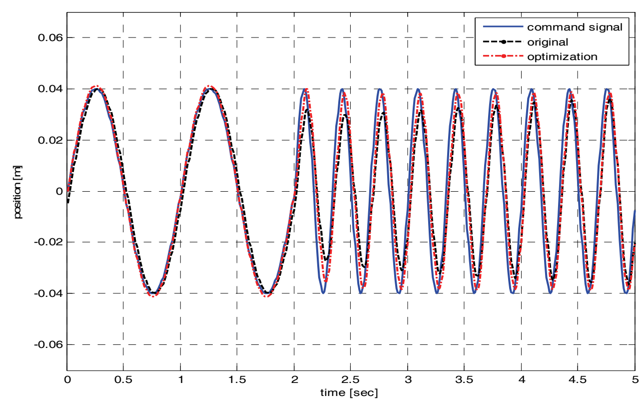


Fig. 7. Experimental results for the comparison of tracking efficiency between the original and the optimized controllers.

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