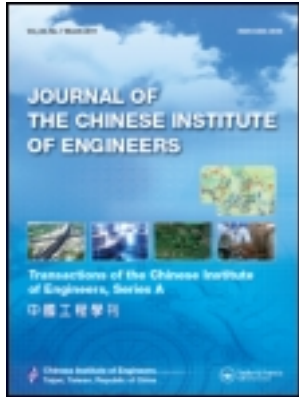


This article was downloaded by: [National Chiao Tung University 國立交通大學]

On: 27 April 2014, At: 17:22

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of the Chinese Institute of Engineers

Publication details, including instructions for authors and subscription information:
<http://www.tandfonline.com/loi/tcie20>

Adaptive backstepping motion control of induction motor drives

Shir-Kuan Lin^a & Chih-Hsing Fang^b

^a Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu, Taiwan, 300, R.O.C.

^b Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu, Taiwan, 300, R.O.C. Phone: 886-3-5918532; Fax: 886-3-5918532; E-mail:

Published online: 04 Mar 2011.

To cite this article: Shir-Kuan Lin & Chih-Hsing Fang (2004) Adaptive backstepping motion control of induction motor drives, Journal of the Chinese Institute of Engineers, 27:3, 449-454, DOI: [10.1080/02533839.2004.9670892](https://doi.org/10.1080/02533839.2004.9670892)

To link to this article: <http://dx.doi.org/10.1080/02533839.2004.9670892>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

Short Paper

ADAPTIVE BACKSTEPPING MOTION CONTROL OF INDUCTION MOTOR DRIVES

Shir-Kuan Lin and Chih-Hsing Fang*

ABSTRACT

In this paper, an adaptive backstepping controller is proposed for position tracking of a mechanical system driven by an induction motor. The mechanical system is a single link fixed on the shaft of the induction motor such as a single-link robot. The backstepping methodology provides a simpler design procedure for an adaptive control scheme and provides a method to define the sliding surface if the robust sliding-mode control is applied. Thus, the backstepping control can be easily extended to work as an adaptive sliding-mode controller. The presented position control system is shown to be stable and robust to parameter variations and external disturbances. The effectiveness of the proposed controllers is demonstrated in experiments.

Key Words: adaptive backstepping control, sliding-mode control, induction motor.

I. INTRODUCTION

Featuring simple construction, ruggedness reliability, and minimum maintenance, induction motors have been widely used in many industry applications and recently even in the field of robotic applications (Hu *et al.*, 1996). In such applications the mechanical load driven by an induction motor must track a time-varying trajectory that specifies its desired positions (Fusco, 2001). To counteract these variations, analyzing and designing the tracking performance of a position controller for a torque-regulated induction motor is proposed in this paper.

A high performance motor drive must have good position command tracking and load regulating response. In real practice, the induction motor drive is influenced by uncertainties, which are usually composed of unpredictable plant parameter variations, external load disturbances, unmodelled and nonlinear dynamics of the plant. Nonlinear control approaches have been developed to deal with such problems. The model reference adaptive parameter variation problems (Ko and Jeon, 1996). The other method is adaptive backstepping control (Jankovic, 1997). The latter is

simpler in its control design procedure. To compensate for uncertainties, much work has been done to develop sliding-mode control schemes (Xia *et al.*, 2000).

In this paper, a new adaptive backstepping position control scheme is developed. The backstepping control method consists of applying a single-variable control scheme to a multivariable control system. It first handles one variable while assuming the other variables can be assigned arbitrarily. Then, the rest of the state equations, with the other variables, are treated by the same procedure. The main contribution of this paper is to develop an adaptive sliding-mode backstepping position controller for a mechanical system driven by an induction motor. This paper emphasizes the motion control of a mechanical system, for a high performance torque control induction motor. For full information about the torque control scheme, the reader is referred to (Lin and Fang, 2001). Our proposed motion control scheme combines adaptive backstepping and sliding-mode technology, so that it can adaptively tune the control gains with respect to changes in the system parameters and can also compensate for uncertainties. The resulting control law provides a method to assign the sliding surfaces for designing sliding-mode control. This special feature of the backstepping control methodology is demonstrated in this paper. The robustness of the proposed control scheme will be verified by an experiment with a sinusoidal disturbance.

*Corresponding author. (Tel: 886-3-5918532; Fax: 886-3-5820050; Email: erict@itri.org.tw)

The authors are with the Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R.O.C.

II. REVISITING A TORQUE CONTROL LAW

This section briefly reviews the sliding-mode torque control scheme, which is adopted as the inner loop of the overall control system. The details of this torque control scheme are presented in (Lin and Fang, 2001). The mathematical model of a three-phase, Y -connected induction motor in a stator-fixed frame (α_s, β_s) can be described by five nonlinear differential equations with four electrical variables [stator currents ($i_{\alpha_s}, i_{\beta_s}$) and rotor fluxes ($\varphi_{\alpha_r}, \varphi_{\beta_r}$)], a mechanical variable [rotor speed (ω_m)], and two control variables [stator voltages ($u_{\alpha_s}, u_{\beta_s}$)] (Novotny and Lipo, 1996) as follows:

$$\dot{i}_{\alpha_s} = -\gamma i_{\alpha_s} + \frac{K}{\tau_r} \varphi_{\alpha_r} + pK\omega_m \varphi_{\beta_r} + \alpha u_{\alpha_s} \quad (1)$$

$$\dot{i}_{\beta_s} = -\gamma i_{\beta_s} + \frac{K}{\tau_r} \varphi_{\beta_r} - pK\omega_m \varphi_{\alpha_r} + \alpha u_{\beta_s} \quad (2)$$

$$\dot{\varphi}_{\alpha_r} = \frac{M}{\tau_r} i_{\alpha_s} - \frac{1}{\tau_r} \varphi_{\alpha_r} - p\omega_m \varphi_{\beta_r} \quad (3)$$

$$\dot{\varphi}_{\beta_r} = \frac{M}{\tau_r} i_{\beta_s} - \frac{1}{\tau_r} \varphi_{\beta_r} + p\omega_m \varphi_{\alpha_r} \quad (4)$$

$$\dot{\omega}_m = -\frac{B}{J} \omega_m + \frac{T_e}{J} - \frac{T_L}{J} \quad (5)$$

where R_s and R_r are the stator and rotor resistance, L_s, L_r , and M are respectively the stator, rotor, and mutual inductance, B and J are the friction coefficient and the moment of inertia of the motor, T_e and T_L are the electromagnetic torque and external load torque, $\tau_r = L_r/R_r$ is the rotor time constant, and the parameters are defined as $\sigma = 1 - M^2/(L_s L_r)$, $K = M/(\sigma L_s L_r)$, $\gamma = R_s/(\sigma L_s) + R_r M^2/(\sigma L_s L_r^2)$, and $\alpha = 1/(\sigma L_s)$. Note that

$$T_e = k_T (i_{\beta_s} \varphi_{\alpha_r} - i_{\alpha_s} \varphi_{\beta_r}) \quad (6)$$

where $k_T = (3P/4)(M/L_r)$, P is the number of pole-pairs.

The torque control scheme is to construct a voltage controller $\mathbf{u} = [u_{\alpha_s} \ u_{\beta_s}]^T$ to ensure that the electromagnetic torque T_e follows the desired torque trajectory T_{eref} . The sliding-mode torque control scheme (Lin and Fang, 2001) proposes to use

$$\mathbf{u} = -\mathbf{D}^{-1} \left(\mathbf{b} + k_c \mathbf{s} + \begin{bmatrix} \mu_{c1} \text{Sat}(s_1) \\ \mu_{c2} \text{Sat}(s_2) \end{bmatrix} \right) \quad (7)$$

where $\mathbf{s} = [s_1, s_2]^T$ are the sliding surfaces of torque and flux, \mathbf{D} , \mathbf{b} , k_c , and (μ_{c1}, μ_{c2}) are the nonlinear control factors that are defined in detail in (Lin and Fang, 2001). Note that the saturation function $\text{Sat}(s_i)$ is defined as

$$\text{Sat}(s_i) = \frac{s_i}{|s_i| + \lambda} \quad (8)$$

where λ is a smooth factor.

Furthermore, the flux observer (Lin and Fang, 2001) is

$$\dot{\hat{i}}_{\alpha_s} = -\gamma \hat{i}_{\alpha_s} + \frac{K}{\tau_r} \hat{\varphi}_{\alpha_r} + pK\omega_m \hat{\varphi}_{\beta_r} + \alpha u_{\alpha_s} + \Lambda_1 \quad (9)$$

$$\dot{\hat{i}}_{\beta_s} = -\gamma \hat{i}_{\beta_s} + \frac{K}{\tau_r} \hat{\varphi}_{\beta_r} + pK\omega_m \hat{\varphi}_{\alpha_r} + \alpha u_{\beta_s} + \Lambda_2 \quad (10)$$

$$\dot{\hat{\varphi}}_{\alpha_r} = \frac{M}{\tau_r} \hat{i}_{\alpha_s} - \frac{1}{\tau_r} \hat{\varphi}_{\alpha_r} - p\omega_m \hat{\varphi}_{\beta_r} + \Lambda_3 \quad (11)$$

$$\dot{\hat{\varphi}}_{\beta_r} = \frac{M}{\tau_r} \hat{i}_{\beta_s} - \frac{1}{\tau_r} \hat{\varphi}_{\beta_r} + p\omega_m \hat{\varphi}_{\alpha_r} + \Lambda_4 \quad (12)$$

where $\hat{i}_{\alpha_s}, \hat{i}_{\beta_s}, \hat{\varphi}_{\alpha_r}, \hat{\varphi}_{\beta_r}$ are the estimators of $i_{\alpha_s}, i_{\beta_s}, \varphi_{\alpha_r}, \varphi_{\beta_r}$, respectively. Let the estimate errors be $\mathbf{e} = [e_1, e_2, e_3, e_4]^T = [\hat{i}_{\alpha_s} - i_{\alpha_s}, \hat{i}_{\beta_s} - i_{\beta_s}, \hat{\varphi}_{\alpha_r} - \varphi_{\alpha_r}, \hat{\varphi}_{\beta_r} - \varphi_{\beta_r}]^T$. The estimate inputs are

$$\begin{cases} \Lambda_1 = -\hat{\rho}_1 \text{sign}(e_1) - \tilde{\zeta}_1 \\ \Lambda_2 = -\hat{\rho}_2 \text{sign}(e_2) - \tilde{\zeta}_2 \end{cases} \quad (13)$$

$$\begin{bmatrix} \Lambda_3 \\ \Lambda_4 \end{bmatrix} = \begin{bmatrix} k_\phi & -p\omega_m \\ p\omega_m & k_\phi \end{bmatrix} \begin{bmatrix} \frac{K}{\tau_r} & pK\omega_m \\ -pK\omega_m & \frac{K}{\tau_r} \end{bmatrix}^{-1} \begin{bmatrix} \Lambda_1 \\ \Lambda_2 \end{bmatrix} - \begin{bmatrix} \rho_3 \text{Sat}(e_3) \\ \rho_4 \text{Sat}(e_4) \end{bmatrix} \quad (14)$$

where the adaptive laws are

$$\dot{\hat{\rho}} = \hat{\rho} = \begin{bmatrix} \hat{\rho}_1 \\ \hat{\rho}_2 \end{bmatrix} = \begin{bmatrix} |e_1| \\ |e_2| \end{bmatrix} \quad (15)$$

$$\dot{\tilde{\zeta}} = \tilde{\zeta} = \begin{bmatrix} \tilde{\zeta}_1 \\ \tilde{\zeta}_2 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_1 \end{bmatrix} \quad (16)$$

and, k_ϕ is a constant and $[\rho_3, \rho_4]$ are the upper bounds of the uncertainty of estimate flux equations.

Then, the estimated torque (\hat{T}_e) and estimated flux ($\hat{\varphi}_\phi$) are calculated as follows,

$$\hat{T}_e = k_T (i_{\beta_s} \hat{\varphi}_{\alpha_r} - i_{\alpha_s} \hat{\varphi}_{\beta_r}) \quad (17)$$

$$\hat{\varphi}_\phi = \sqrt{\hat{\varphi}_{\alpha_r}^2 + \hat{\varphi}_{\beta_r}^2} \quad (18)$$

and the result of estimated signals are used as the sliding-mode torque controller of feedback signals.

III. ADAPTIVE BACKSTEPPING MOTION CONTROL

This paper tried to develop a new backstepping control law for motion tracking of an induction motor. The sliding-mode torque control scheme (Lin and Fang, 2001) is implemented as an inner loop of torque control. Fig. 1 shows the control structure with a rod fixed on the shaft axis of the motor which is an example of a single link robot. The following context is then concentrated on the motion tracking of a

mechanical system driven by an induction motor.

The dynamics of the mechanical system are

$$\begin{aligned} J\ddot{\theta}_m &= -B\dot{\theta}_m - mgl \sin(\theta_m + \theta_0) + k_T u_T \\ &= -B\dot{\theta}_m - mgl \cos\theta_0 \sin\theta_m \\ &\quad - mgl \sin\theta_0 \cos\theta_m + k_T u_T \end{aligned} \quad (19)$$

where θ_m is the angular displacement of the shaft, m is the mass of the rod, l is the distance from the shaft center to the center of mass of the rod, g is the gravitational acceleration, and θ_0 is the null angle from the line of gravity. Furthermore, (19) is simplified as

$$\ddot{\theta}_m = -B_J \dot{\theta}_m - (L_b \sin\theta_m + L_c \cos\theta_m) + K_J u_T \quad (20)$$

where $B_J = B/J$, $L_b = mgl \cos\theta_0/J$, $L_c = mgl \sin\theta_0/J$, $K_J = k_T/J$. Note that $J > 0$.

The control objective is to design a controller u_T that forces the position variable θ_m to track a desired trajectory denoted by θ_m^* , which is second-order continuously differentiable. Define the tracking error as $e_p = \theta_m^* - \theta_m$. The system in (20) can be rewritten as

$$\begin{cases} e_s = \dot{e}_p = \dot{\theta}_m^* - \dot{\theta}_m \\ \dot{e}_s = \ddot{e}_p = \ddot{\theta}_m^* + B_J \dot{\theta}_m + (L_b \sin\theta_m + L_c \cos\theta_m) - K_J u_T \end{cases} \quad (21)$$

The concept of the backstepping is first to consider only one of the states. We consider e_p and let the Lyapunov-like function be $V_0 = e_p^2/2$. The derivative of V_0 along the trajectory of e_p is

$$\dot{V}_0 = e_p \dot{e}_p = -c_1 e_p^2 + e_p (e_s + c_1 e_p) \quad (22)$$

The purpose of the special form of (22) is to achieve $\dot{V}_0 = -c_1 e_p^2 < 0$ for $e_p \neq 0$ if e_s were kept to be $-c_1 e_p$. However, e_s cannot be arbitrarily assigned. The backstepping design is then to consider the error $z \equiv e_s - (-c_1 e_p)$. e_s is actually the integrator of e_p . If $-c_1 e_p$ were inserted into the system as a feedback term, then the system would be stable. However, this can be treated by adding $(-c_1 e_p)$ in the position of e_s in the actual system and "backstepping" $(-c_1 e_p)$ through the integrator.

According to (21), the dynamics of z are

$$\dot{z} = K_J (\mathbf{h}^T \bar{\mathbf{x}} - u_T) \quad (23)$$

where

$$\mathbf{h} = \begin{bmatrix} 1/K_J \\ B_J/K_J \\ L_b/K_J \\ L_c/K_J \end{bmatrix}, \quad \bar{\mathbf{x}} = \begin{bmatrix} \dot{\theta}_m^* + c_1(\dot{\theta}_m^* - \dot{\theta}_m) \\ \dot{\theta}_m \\ \sin\theta_m \\ \cos\theta_m \end{bmatrix} \quad (24)$$

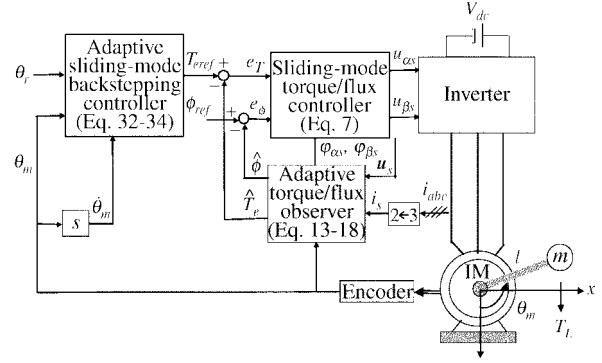


Fig. 1 Overall system of the position control of an induction motor

Note that the parameters of \mathbf{h} are assumed unknown. We need to design an adaptive backstepping controller to estimate these parameters on line. The estimates of the unknown parameters are denoted by $\hat{\mathbf{h}}$ and the estimation error is $\tilde{\mathbf{h}} = \mathbf{h} - \hat{\mathbf{h}}$.

Now, consider a new Lyapunov-like function:

$$V_1 = \frac{1}{2}(e_p^2 + z^2 + K_J \tilde{\mathbf{h}}^T \mathbf{\Gamma} \tilde{\mathbf{h}}) \quad (25)$$

where $\mathbf{\Gamma}$ is a positive definite matrix. The derivative of V_1 along the trajectory of the system, i.e., (21), is

$$\begin{aligned} \dot{V}_1 &= -c_1 e_p^2 + e_p z + z K_J (\mathbf{h}^T \bar{\mathbf{x}} - u_T) + K_J \tilde{\mathbf{h}}^T \mathbf{\Gamma} \dot{\tilde{\mathbf{h}}} \\ &= -\boldsymbol{\varepsilon}^T \mathbf{F} \boldsymbol{\varepsilon} \end{aligned} \quad (26)$$

where

$$\boldsymbol{\varepsilon} = \begin{bmatrix} e_p \\ z \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} c_1 & -1/2 \\ -1/2 & c_2 \end{bmatrix} \quad (27)$$

if the controller and the adaptive laws are, respectively,

$$u_T = \hat{\mathbf{h}}^T \bar{\mathbf{x}} \quad (28)$$

$$\dot{\hat{\mathbf{h}}} = -z \mathbf{\Gamma}^{-1} \bar{\mathbf{x}} \quad (29)$$

where $\bar{\mathbf{x}}^T = \bar{\mathbf{x}}^T + [c_2 z, 0, 0, 0]$. It is easy to show that the symmetrical matrix \mathbf{F} is positive definite and then $\dot{V}_1 \leq 0$ if $c_1 c_2 > 1/4$.

Proposition 1. Consider the system in (20). The angular displacement θ_m of the system will asymptotically converge to the desired trajectory θ_m^* if the controller and the adaptive law are, respectively, (28) and (29) with $c_1 c_2 > 1/4$.

Proof. V_1 in (25) is a Lyapunov-like function, so we cannot directly apply the Lyapunov stability theory.

However, V_1 is bounded below and non-increasing, which implies that $\lim_{t \rightarrow \infty} V_1(t) = V_{1\infty}$ exists (Ioannou and Sun, 1996). Thus, $e_p, z, \tilde{\mathbf{h}} \in L_\infty$, so that $\dot{\tilde{\mathbf{h}}} \in L_\infty$ since \mathbf{h} is constant. It then follows from (21) and (23) that

$e_p, \dot{z} \in L_\infty$. Integrating (26), we obtain $V_1(t)|_{t=0} - V_{1\infty} \geq \int_0^\infty \boldsymbol{\varepsilon}^T \boldsymbol{\Gamma} \boldsymbol{\varepsilon}$, and then $\boldsymbol{\varepsilon} \in L_2$. A corollary of Barbalat's lemma (Ioannou and Sun, 1996) states that $\boldsymbol{\varepsilon} \in L_\infty$ and $\boldsymbol{\varepsilon} \in L_2$ imply $\boldsymbol{\varepsilon} \rightarrow 0$ as $t \rightarrow \infty$. This completes the proof.

It should be remarked that u_T in (28) is used as the reference active torque T_{eref} for the inner loop torque control (see Fig. 1).

IV. ROBUSTNESS

The above mechanical model is an ideal case. We now consider a more practical case by introducing an uncertainty in (20) to obtain

$$\ddot{\theta}_m = -B_J \dot{\theta}_m - (L_b \sin \theta_m + L_c \cos \theta_m) + K_J u_T + \Delta \quad (30)$$

where $\Delta \equiv K_J \Delta_1$ is a bounded uncertainty satisfying $|\Delta_1| \leq \kappa$, in which $\kappa > 0$ is an unknown bound. After introducing the uncertainty, (23) should also be modified as

$$\dot{z} = K_f (\mathbf{h}^T \bar{\mathbf{x}} \dot{\theta} - \Delta_1 - u_T) \quad (31)$$

Let the sliding surface be $s = \boldsymbol{\varepsilon}$ and define the Lyapunov function as $V = (1/2) \mathbf{s}^T \mathbf{s}$. It can be shown that a sliding-mode controller $u_T = \mathbf{h}^T \mathbf{x} + \kappa \text{sign}(z)$ can draw the overall system to the sliding surface $s = 0$ and then θ_m asymptotically approaches the target θ_m^* , if all system parameters are known. However, we assume that the parameters are unknown. Thus, we require the following adaptive sliding-mode backstepping controller.

Proposition 2. Consider the system (30). The angular displacement θ_m of the system will asymptotically converge to the desired trajectory θ_m^* if the controller and the adaptive law are, respectively,

$$u_T = \hat{\mathbf{h}}^T \mathbf{x} + \hat{\kappa} \text{sign}(z) \quad (32)$$

$$\dot{\hat{\mathbf{h}}} = \mathbf{z} \boldsymbol{\Gamma}^{-1} \mathbf{x} \quad (33)$$

$$\dot{\hat{\kappa}} = \gamma_\rho^{-1} |z| \quad (34)$$

with $c_1 c_2 > 1/4$ for \mathbf{x} and $\gamma_\rho > 0$.

Proof. Let the Lyapunov-like function V_2 be

$$V_2 = \frac{1}{2} (\boldsymbol{\varepsilon}^T \boldsymbol{\varepsilon} + K_J \hat{\mathbf{h}}^T \boldsymbol{\Gamma} \hat{\mathbf{h}} + K_J \gamma_\rho \hat{\kappa}^2) \quad (35)$$

where $\hat{\kappa} = \kappa - \tilde{\kappa}$. Applying (32), we obtain the derivative of V_2 along the trajectory of the system (30) as

$$\begin{aligned} \dot{V}_2 &= -\boldsymbol{\varepsilon}^T \boldsymbol{\Gamma} \boldsymbol{\varepsilon} - z K_J (\Delta_1 + \hat{\kappa} \text{sign}(z)) + K_J \gamma_\rho \tilde{\kappa} \dot{\tilde{\kappa}} \\ &\leq -\boldsymbol{\varepsilon}^T \boldsymbol{\Gamma} \boldsymbol{\varepsilon} + K_J (\kappa |z| - \hat{\kappa} |z|) + K_J \gamma_\rho \tilde{\kappa} \dot{\tilde{\kappa}} \\ &= -\boldsymbol{\varepsilon}^T \boldsymbol{\Gamma} \boldsymbol{\varepsilon} \leq 0 \end{aligned} \quad (36)$$

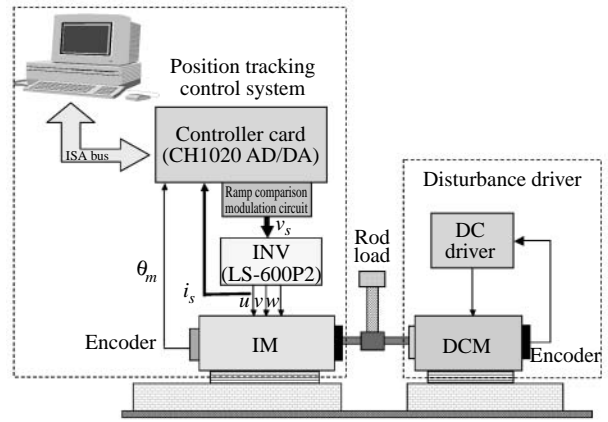


Fig. 2 Experimental system

Note that $-\Delta_1 \leq |\Delta_1 z| \leq \kappa |z|$. Then V_2 is bounded below and non-increasing. The rest of the proof is similar to the last part of the proof of Proposition 1 and is thus omitted.

V. EXPERIMENTS

The experimental system for the proposed adaptive sliding-mode backstepping position control is shown in Fig. 2. This is a PC-based control system and the ramp comparison modulation circuit is to drive the voltage source inverter. The induction motor in the experimental system is a 4-pole, 5HP, 220V motor with the rated current, speed, and torque of 13.4A, 1730rpm, and 18Nm, respectively. The encoder has 4096 counters per revolution. The parameters of the motor are $R_s = 0.3\Omega$, $R_r = 0.36\Omega$, $L_s = L_r = 48$ mH, and $M = 45$ mH. Those of the mechanical system are $J = 0.0069$ kgm², $l \approx 0.45$ m, and $m \approx 3$ kg.

Two experiments are conducted: 1) reference trajectory generated by set-point positions, and 2) robust position control.

In the first experiment, the motor is asked to go to $\theta_m = \pi/2$ at $t = 0.5$ s, then to $\theta_m = \pi$ at $t = 5$ s, and finally to return to $\theta_m = \pi/2$ again at $t = 8$ s. However, the desired trajectory is generated by the reference model of

$$\ddot{\theta}_m^* = -k_t \dot{\theta}_m^* - k_s \theta_m^* + k_s \theta_r \quad (37)$$

where θ_r is the angular displacement command, and k_t , and k_s are positive constants, which can be selected such that $s^2 + k_t s + k_s = (s + p_1)(s + p_2)$ with $p_1, p_2 > 0$. The gains of the reference model are $k_t = 10$ and $k_s = 30$. It should be remarked that the reference torque T_{Tref} in the inner loop is generated by the adaptive sliding-mode backstepping controller stated in Proposition 2, while the reference flux ϕ_{ref} is given as a constant of 0.43 Wb. The experimental results are shown in Fig. 3. It can be seen that the steady-state error is negligible, and the transient response also meets the reference model standard. The history of the estimated torque shows that the values are

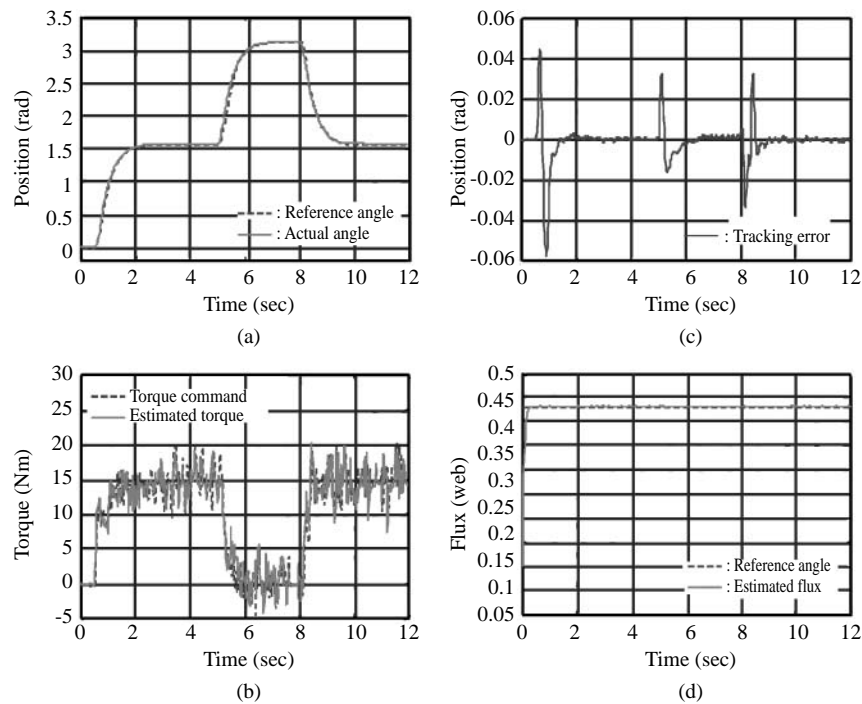


Fig. 3 Responses of a set point positions command: (a) position; (b) torque command and estimated torque; (c) tracking error ($\theta_m^* - \theta_m$); (d) rotor flux

around zero for $\theta_m = \pi$ and around 14Nm for $\theta_m = \pi/2$, which is consistent with the physical property.

The second experiment asks the motor to go to $\theta_m = \pi/2$ at $t = 0.5$ s. The desired trajectory is also generated by (37). However, there is disturbance torque $T_L = 3.5\sin 2(t-3)$ Nm, $\forall t \geq 3$, beginning at $t = 3$ s, which is generated by an external DC-motor. The experimental results for the control laws in Propositions 1 and 2 are shown in Fig. 4. It can be seen that the adaptive sliding-mode backstepping controller can compensate for the sinusoidal disturbance, whereas the control law in Proposition 1 cannot. This verifies the robustness of the proposed control law in Proposition 2.

VI. CONCLUSIONS

This paper presents a new adaptive backstepping motion control for a mechanical system driven by an induction motor. We adopt the sliding-mode torque control proposed in Lin and Fang (2001) as the inner loop controller, which ensures that the electromagnetic torque of the motor will closely follow the torque command. The main point of this paper is then to design a position controller, which generates the torque command to the inner loop controller so that asymptotic stability can be ensured. This position controller is derived from backstepping methodology. On the other hand, the backstepping method provides a way to define the sliding surface for the sliding-mode control. That is to define the sliding surface functions as state variables of the backstepping control system,

such as ε in Eq. (27). We use this concept to deal with a system containing an uncertainty. The proposed control scheme is the so-called adaptive sliding-mode backstepping controller stated in Proposition 2. The control system is implemented on a PC-based system to control an induction motor with a rod fixed on the shaft. Both set-point and tracking position control experiments verify the control theory and show that the proposed control scheme is useful for industrial applications.

ACKNOWLEDGMENTS

This paper was, in part, supported by the National Science Council, Taiwan under Grant No. NSC90-2212-E-009-063.

NOMENCLATURE

$\hat{}$	estimated quantities
$*$	commanded or reference quantities
\sim	error quantities
B	friction coefficient
c_1, c_2	control gains
e	estimate errors
e_p, e_s	displacement and speed tracking errors
g	gravitational acceleration
h	adaptive backstepping parameters
$i_{\alpha s}, i_{\beta s}$	stator currents in the stationary frame
J	the moment of inertia of the motor
k_T	torque gain

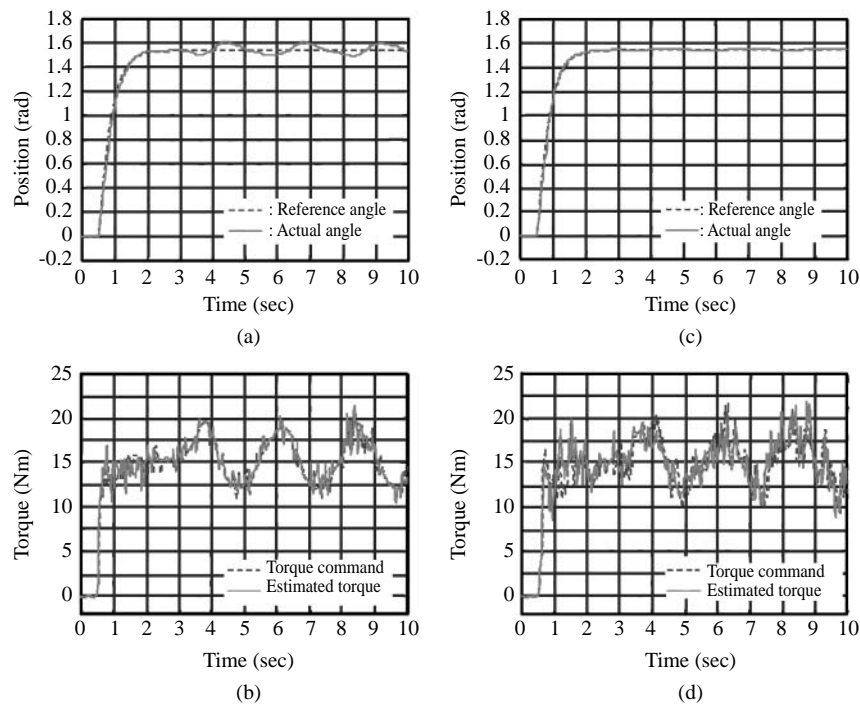


Fig. 4 Responses of a set point position command: in the adaptive backstepping controller: (a) position; (b) torque command and estimated torque; in the adaptive sliding-mode backstepping controller: (c) position; (d) torque command and estimated torque

k_t, k_s	gains of reference model
l	shaft length
L_s, L_r, M	stator, rotor, and mutual inductance
m	mass of the rod
p_1, p_2	poles of reference model
R_s, R_r	stator and rotor resistance
s	laplace expression symbol
s	sliding surfaces
T_e, T_L	electromagnetic torque and external load
u	voltage controller
$u_{\alpha s}, u_{\beta s}$	stator voltages in the stationary frame
\bar{x}	adaptive backstepping input signal
z	backstepping error
Δ, Δ_1	uncertainty bounded
θ_m	angular displacement of the shaft
θ_0	null angle
$\Lambda_1, \dots, \Lambda_4$	estimate inputs
τ_r	rotor time constant
$\varphi_{\alpha r}, \varphi_{\beta r}$	rotor fluxes in the stationary frame
ω_m	rotor speed

REFERENCES

- Fusco, G., 2001, "Tracking Performance of an H_∞ Position Controller for Current-Fed Induction Motors under Mechanical Load Variations," *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Como, Italy, Vol. 2, pp. 713-718.
- Hu, J., Dawson, D. M., and Qian, Z., 1996, "Position

Tracking Control for Robot Manipulators Driven by Induction Motors without Flux Measurements," *IEEE Transactions on Robotics and Automation*, Vol. 12, No. 3, pp. 419-438.

- Ioannou, P. A., and Sun, J., 1996, *Robust Adaptive Control*, Prentice-Hall, Upper Saddle River, NJ, USA.
- Jankovic, M., 1997, "Adaptive Nonlinear Output Feedback Tracking with a Partial High-Gain Observer and Backstepping," *IEEE Transactions on Automatic Control*, Vol. 42, No. 1, pp. 106-113.
- Ko, J. S., and Jeon, C. H., 1996, "New MRAC Load Torque Observer for the Position Control of BLDC Motor," *Proceedings of the IEEE International Conference on Industrial Technology*, (ICIT '96), Shanghai, China, pp. 565-569.
- Lin, S. K., and Fang, C. H., 2001, "Sliding-Mode Direct Torque Control of an Induction Motor," *The 27th Annual Conference of the IEEE Industrial Electronics Society*, (IECON'01), Vol. 3, pp. 2171-2177.
- Novotny, D. W., and Lipo, T. A., 1996, *Vector Control and Dynamics of AC Drives*, Oxford Press, New York, USA.
- Xia, Y., Yu, X., and Oghanna, W., 2000, "Adaptive Robust Fast Control for Induction Motors," *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 4, pp. 854-862.

Manuscript Received: Feb. 17, 2003

Revision Received: Jun. 17, 2003

and Accepted: Aug. 29, 2003