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交流感應馬達之適應性回步階運動控制

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交流感應馬達之適應性回步階運動控制
Adaptive Backstepping Motion Control of Induction Motors

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1 Abstract

In this project, 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.

Keywords: Adaptive Backstepping Control, Sliding-Mode Control, Induction Motor.

中文摘要

本研究計畫針對機械驅動系統之感應馬達位置追蹤，提出適應性回步階運動控制之研究，機械運動負載為馬達軸承上固定一單軸聯桿機構如單軸機器人為研究對象。適應性回步階控制具較簡單的適應控制設計程序，另其特性可推演出滑動平面，進而可加入具強健性之滑動模式控制，設計出適應滑動模式適應性回步階控制法則，運用於位置控制系統，除具穩定特性，並對參數變動、外在負載擾動與非線性模式皆加強其強健性，經由實驗可證明所提控制策略的有效性。

關鍵詞：適應性回步階、滑動模式、感應馬達

2 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 [1]. In such applications the mechanical load driven by an induction motor must track a time-varying trajectory that specifies its desired positions [2]. To counteract these variations, analyzing and designing the tracking performance of a position controller for a torque-regulated induction motor is proposed in this project.

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 control (MRAC) technique is one method to overcome parameter variation problems [4]. The other method is adaptive backstepping control [5]. The latter is simpler in its control design procedure. To compensate for uncertainties, much work has been done to develop sliding-mode control schemes [8].

In this project, 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 eqations, with the other variables, are treated by the same procedure. The main contribution of this project is to develop an adaptive sliding-mode backstepping position controller for a mechanical system driven by an induction motor. This project 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 refered to [6]. 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 project. The robustness of the proposed control scheme will be verified by an experiment with a sinusoidal disturbance.

3 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 [6]. The mathematical model of a three-phase, Y-connected induction motor in a stator-fixed frame ($\alpha s, \beta s$) 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 ($u_\alpha, u_{\beta r}$)] [7] as follows:

$$\dot{i}_{\alpha s} = -\gamma i_{\alpha s} + \frac{K}{T_r}\varphi_{\alpha r} + pK\omega\varphi_{\beta r} + \alpha u_{\alpha s} \quad (1)$$

$$\dot{i}_{\beta s} = -\gamma i_{\beta s} + \frac{K}{T_r}\varphi_{\beta r} - pK\omega\varphi_{\alpha r} + \alpha u_{\beta s} \quad (2)$$

$$\dot{\varphi}_{\alpha r} = \frac{M}{T_r} i_{\alpha s} - \frac{1}{T_r}\varphi_{\alpha r} - p\omega\varphi_{\beta r} \quad (3)$$

$$\dot{\varphi}_{\beta r} = \frac{M}{T_r} i_{\beta s} - \frac{1}{T_r}\varphi_{\beta r} + p\omega\varphi_{\alpha r} \quad (4)$$

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

where R_s and R_r are the stator and rotor resistance, L_s, L_r, and M are the stator, rotor, and mutual inductance, B and J are the friction coefficient and the moment of inertial 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, the parameters are $\sigma \equiv 1 - M^2/(L_s L_r)$, $K \equiv M/(\sigma L_s L_r)$, $\alpha \equiv 1/(\sigma L_s)$, and $\gamma \equiv R_s/(\sigma L_s) + R_r M^2/(\sigma L_s L_r^2)$. Note that

$$T_e = k_T(i_{\beta s}\varphi_{\alpha r} - i_{\alpha s}\varphi_{\beta r}) \quad (6)$$

where $k_T \equiv (3P/4)(M/L_r)$, 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 [6] proposes to use

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

where $\mathbf{s} = [s_1,\ s_2]^T$ are the sliding surfaces of torque and flux, $\mathbf{D}$, $\mathbf{b}$, k_c, and $(\mu_{c1},\ \mu_{c2})$ are the nonlinear control factors that are defined in detail in [6]. Note that the saturation function $\mathrm{Sat}(s_i)$ is defined as

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

where $\lambda > 0$ is a smooth factor.

Furthermore, the flux observer [6] is

$$\begin{aligned} \dot{\hat{i}}_{\alpha s} &= -\gamma\hat{i}_{\alpha s} + \frac{K}{T_r}\hat{\varphi}_{\alpha r} + pK\omega\hat{\varphi}_{\beta r} \\ &\quad + \alpha u_{\alpha s} + \Lambda_1 \end{aligned} \quad (9)$$

$$\begin{aligned} \dot{\hat{i}}_{\beta s} &= -\gamma\hat{i}_{\beta s} + \frac{K}{T_r}\hat{\varphi}_{\beta r} - pK\omega\hat{\varphi}_{\alpha r} \\ &\quad + \alpha u_{\beta s} + \Lambda_2 \end{aligned} \quad (10)$$

$$\dot{\hat{\varphi}}_{\alpha r} = \frac{M}{T_r}\hat{i}_{\alpha s} - \frac{1}{T_r}\hat{\varphi}_{\alpha r} - p\omega\hat{\varphi}_{\beta r} + \Lambda_3 \quad (11)$$

$$\dot{\hat{\varphi}}_{\beta r} = \frac{M}{T_r}\hat{i}_{\beta s} - \frac{1}{T_r}\hat{\varphi}_{\beta r} + p\omega\hat{\varphi}_{\alpha r} + \Lambda_4 \quad (12)$$

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

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

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

where the adaptive laws are

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

$$\dot{\tilde{\boldsymbol{\zeta}}} = \dot{\hat{\boldsymbol{\zeta}}} = \begin{bmatrix} \dot{\hat{\zeta}}_1 \\ \dot{\hat{\zeta}}_2 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \quad (16)$$

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

4 Adaptive Backstepping Motion Control

This project tried to develop a new backstepping control law for motion tracking of an induction motor. The sliding-mode torque control scheme [6] 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

$$\begin{aligned} J\ddot{\theta}_m &= -B\dot{\theta}_m - mgl\sin(\theta_m+\theta_0) + k_T u_T \\ &= -B\dot{\theta}_m - mgl\cos\theta_0\sin\theta_m \\ &\quad -mgl\sin\theta_0\cos\theta_m + k_T u_T \end{aligned} \quad (17)$$

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, (17) is simplified as

$$\ddot{\theta}_m = -B_J\dot{\theta}_m - L_s\sin\theta_m - L_c\cos\theta_m + K_J u_T \quad (18)$$

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

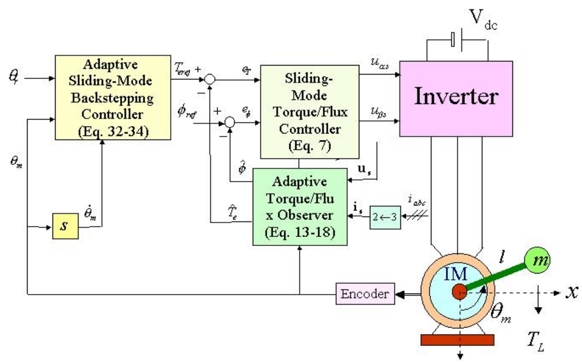

Fig. 1: Overall system of the position control of an induction motor.

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 secon-order continuously differentiable. Define the tracking error as $e_p = \theta_m^* - \theta_m$. The system in (18) can be rewritten as

$$\begin{cases} \dot{e}_p = e_s = \dot{\theta}_m^* - \dot{\theta}_m \\ \dot{e}_s = \ddot{e}_p = \ddot{\theta}_m^* + B_J\dot{\theta}_m + L_s\sin\theta_m \\ \qquad + L_c\cos\theta_m - K_J u_T \end{cases} \quad (19)$$

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

$$\dot{V}_0 = e_p\dot{e}_p = -c_1 e_p^2 + e_p(e_s + c_1 e_p) \quad (20)$$

The purpose of the special form of (20) 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 $z \equiv e_s - (-c_1 e_p)$. According to (19), the dynamics of z are

$$\dot{z} = K_J\left(\mathbf{h}^T\bar{\mathbf{x}} - u_T\right) \quad (21)$$

where

$$\mathbf{h} = \begin{bmatrix} 1/K_J \\ B_J/K_J \\ L_s/K_J \\ L_c/K_J \end{bmatrix}, \quad \bar{\mathbf{x}} = \begin{bmatrix} \ddot{\theta}_m^* + c_1(\dot{\theta}_m^* - \dot{\theta}_m) \\ \dot{\theta}_m \\ \sin\theta_m \\ \cos\theta_m \end{bmatrix} \quad (22)$$

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:

$$V_1 = \frac{1}{2}\left(e_p^2 + z^2 + K_J\tilde{\mathbf{h}}^T\mathbf{\Gamma}\tilde{\mathbf{h}}\right) \quad (23)$$

where $\mathbf{\Gamma}$ is a positive definite matrix. The derivative of V_1 along the trajectory of the system (19) is

$$\begin{aligned} \dot{V}_1 &= -c_1 e_p^2 + e_p z + zK_J\left(\mathbf{h}^T\bar{\mathbf{x}} - u_T\right) + K_J\tilde{\mathbf{h}}^T\mathbf{\Gamma}\dot{\tilde{\mathbf{h}}} \\ &= -\boldsymbol{\varepsilon}^T\mathbf{F}\boldsymbol{\varepsilon} \end{aligned} \quad (24)$$

where

$$\boldsymbol{\varepsilon} = \begin{bmatrix} e_p \\ z \end{bmatrix}, \qquad \mathbf{F} = \begin{bmatrix} c_1 & -1/2 \\ -1/2 & c_2 \end{bmatrix} \quad (25)$$

if the controller and the adaptive law are, respectively,

$$u_T = \hat{\mathbf{h}}^T\mathbf{x} \quad (26)$$

$$\dot{\hat{\mathbf{h}}} = z\mathbf{\Gamma}^{-1}\mathbf{x} \quad (27)$$

where $\mathbf{x}^T = \bar{\mathbf{x}}^T + [c_2 z, \ 0, \ 0, \ 0]$. 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 (18). 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, (26) and (27) with $c_1 c_2 > 1/4$.

Proof. V_1 in (23) 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 $\lim_{t\to\infty} V(t)_1 = V_{1\infty}$ exists [3]. Thus, e_p, z, $\tilde{\mathbf{h}} \in L_\infty$, so that $\hat{\mathbf{h}} \in L_\infty$ since $\mathbf{h}$ is constants. It then follows from (19) and (21) that $\dot{e_p}$,$\dot{z} \in L_\infty$. Integrating (24), we obtain $V_1(t)|_{t=0} - V_{1\infty} \geq \int_0^\infty \boldsymbol{\varepsilon}^T\mathbf{\Gamma}\boldsymbol{\varepsilon}$, and then $\boldsymbol{\varepsilon} \in L_2$. A corollary of Barbalat's lemma [3] states that $\boldsymbol{\varepsilon} \in L_\infty$ and $\boldsymbol{\varepsilon} \in L_2$ imply $\boldsymbol{\varepsilon} \to \mathbf{0}$ as $t \to \infty$. This completes the proof. Q.E.D.

It should be remarked that u_T in (26) is used as the reference active torque u_{Tref} for the inner loop torque control (see Fig. 1).

5 Extension to Robustness

The above mechanical model is an ideal case. We now consider a more practical case by introducing an uncertainty in (18) to obtain

$$\ddot{\theta}_m = -B_J\dot{\theta}_m - L_s \sin\theta_m - L_c \cos\theta_m + K_J u_T + \Delta \tag{28}$$

where $\Delta \equiv K_J\Delta_1$ is a bounded uncertainty satisfying $|\Delta_1| \le \rho$, in which $\rho > 0$ is an unknown bound. After introducing the uncertainty, (21) should also be modified as

$$\dot{z} = K_J\left(\mathbf{h}^T\bar{\mathbf{x}} - \Delta_1 - u_T\right) \tag{29}$$

Let the sliding surface be $\mathbf{s} = \boldsymbol{\varepsilon}$ and define the Lyapunov function as $V = (1/2)\mathbf{s}^T\mathbf{s}$. It can be shown that a sliding-mode controller $u_T = \mathbf{h}^T\mathbf{x} + \rho\ \mathrm{sign}(z)$ can draw the overall system to the sliding surface $\mathbf{s} = \mathbf{0}$ 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 (28). 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,

$$u_T = \hat{\mathbf{h}}^T\mathbf{x} + \hat{\rho}\ \mathrm{sign}(z) \tag{30}$$

$$\dot{\hat{\mathbf{h}}} = z\boldsymbol{\Gamma}^{-1}\mathbf{x} \tag{31}$$

$$\dot{\hat{\rho}} = \gamma_\rho^{-1}|z| \tag{32}$$

with $c_1c_2 > 1/4$ for $\mathbf{x}$ and $\gamma_\rho > 0$.

Proof. Let the Lyapunov-like function V_2 be

$$V_2 = \frac{1}{2}\left(\boldsymbol{\varepsilon}^T\boldsymbol{\varepsilon} + K_J\tilde{\mathbf{h}}^T\boldsymbol{\Gamma}\tilde{\mathbf{h}} + K_J\gamma_\rho\tilde{\rho}^2\right) \tag{33}$$

where $\tilde{\rho} = \rho - \hat{\rho}$. Applying (30), we obtain the derivative of V_2 along the trajectory of the system (28) as

$$\begin{aligned} \dot{V}_2 &= -\boldsymbol{\varepsilon}^T\mathbf{F}\boldsymbol{\varepsilon} - zK_J(\Delta_1 + \hat{\rho}\ \mathrm{sign}(z)) + K_J\gamma_\rho\tilde{\rho}\dot{\tilde{\rho}} \\ &\le -\boldsymbol{\varepsilon}^T\mathbf{F}\boldsymbol{\varepsilon} + K_J(\rho|z| - \hat{\rho}|z|) + K_J\gamma_\rho\tilde{\rho}\dot{\tilde{\rho}} \\ &= -\boldsymbol{\varepsilon}^T\mathbf{F}\boldsymbol{\varepsilon} \le 0 \end{aligned} \tag{34}$$

Note that $-\Delta_1 z \le |\Delta_1 z| \le \rho|z|$. 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 omitted. Q.E.D.

6 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 $R_s = 0.3\Omega$, $R_r = 0.36\Omega$, $L_s = 48mH$, $L_r = 48mH$, and $L_m = 45mH$. Those of the mechanical system are $J \approx 0.0042\text{kgm}^2$, $l \approx 0.5$m, and $m \approx 1.7$kg.

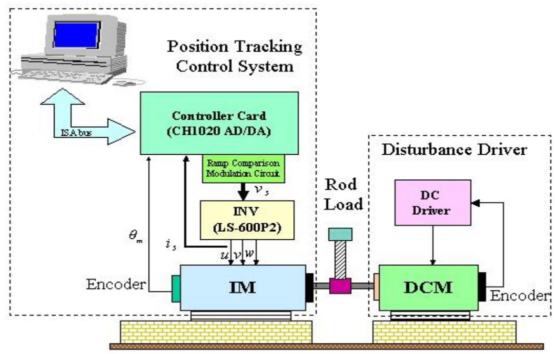

Fig. 2: Experimental system.

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

$$\ddot{\theta}_m^* = -k_t\dot{\theta}_m^* - k_s\theta_m^* + k_s\theta_r \tag{35}$$

where θ_r is the angular displacement command, and k_t and k_s are positive constants, which can be selected that $s^2 + k_ts + k_s = (s + p_1)(s + p_2)$ with $p_1, p_2 > 0$. The gains of the reference model are $k_t = 10$ and $k_s = 24$. It should be remarked that the reference active torque u_{Tref} in the inner loop is equal to u_T 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 experiment 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. The history of the estimated torque shows that the values are around zero for $\theta_m = \pi$ and around about 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 (35). However, there is disturbance torque $T_l = 3.5sin2(t-3)$Nm, $\forall t > 0$, 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.

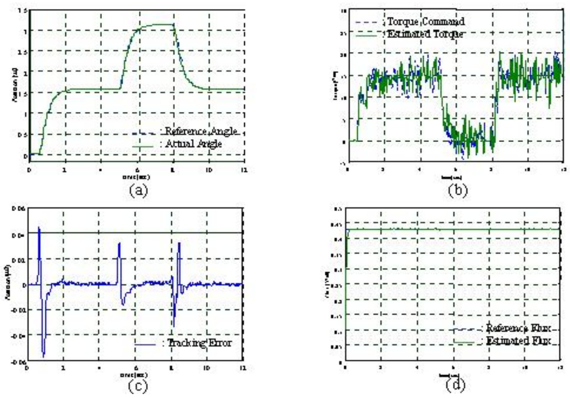

Fig. 3: Responses of a set point positions command: (a) position; (b) torque command and estimated torque; (c) tracking error ($\theta_m^* - \theta_m$); (d) rotor flux.

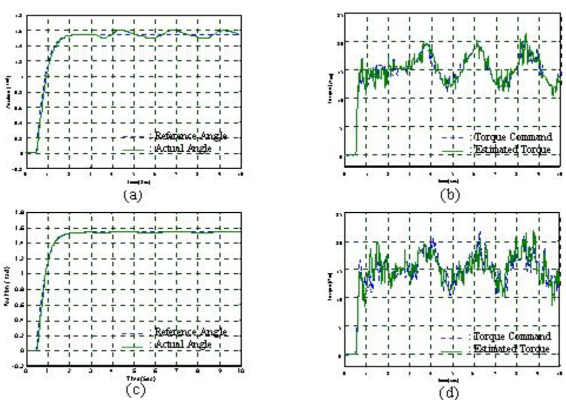

Fig. 4: Responses of a set point position command: in the adaptive backstepping controller: (a) position; (b) torque command and estimated torque; in the adaptive sliding-mode backstepping controller: (c) position; (d) torque command and estimated torque

7 Conclusion

This project presents a new adaptive backstepping motion control for a mechanical system driven by an induction motor. We adopt the sliding-mode direct torque control proposed in [6] as the inner loop controller, which ensures that the electromagnetic torque of the motor will closely follow the torque command. The main topic of this project is then only to design a position controller, which generates the torque command to the inner loop controller so that the asymptotical stability can be ensured. This position controller is derived based on the backstepping methodology. On the other hand, the backstepping method provides a way to define the sliding surface for the sliding-mode control. We use this concept to extend the result to the system with 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.

References

[1] Hu J., D.M. Dawson, and Z. Qian, "Position tracking control for robot manipulators driven by induction motors without flux measurements," *IEEE Trans. Robotics Automatic*, vol. 12, pp. 419-438, 1996.

[2] Fusco, G., "Tracking performance of an H_∞ position controller for current-fed induction motors under mechanical load variations," *IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics Proc., Como, Italy*, pp. 713-718, 2001.

[3] Ioannou, P.A. and J. Sun, *Robust Adaptive Control.* Prentice-Hall Press, 1996.

[4] Ko, J.S. and C.H. Jeon, "New MRAC load torque observer for the position control of BLDC motor," *Proc. IEEE Int. Conf. on Industrial Technology, (ICIT '96)*, pp. 565 -569, 1996.

[5] Jankovic, M., "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, 1997.

[6] Lin, S.K. and C.H. Fang, "Sliding-mode direct torque control of an induction motor," *The 27th Annual Conference of the IEEE Industrial Electronics Societ*, pp. 2171-2177, 2001.

[7] Novotny, D.W. and T.A. Lipo, *Vector control and dynamics of AC drives.* Oxford Press, 1996.

[8] Xia, Y., X. Yu, and W. Oghanna, "Adaptive robust fast control for induction motors," *IEEE Trans. Ind. Electronic*, vol. 47, pp. 854 -862, 2000.