Microprocessor-Based Adjustable-Speed DC Motor Drives Using Model Reference Adaptive Control

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Abstract—**Model reference adaptive control (MRAC) is applied to microprocessor-based adjustable-speed dc motor drives. The algorithm of the MRAC is based on the linear model following control (LMFC) and is the combination of the adaptive controller with the LMFC. The MRAC-based speed controller allows the indistinctness and/or inaccuracy in the motor and load parameters in the system design stage. It also maintains the prescribed control performance in the presence of the motor parameter perturbations and the load disturbances. The experimental setup is constructed using a microprocessor. The experimental results confirm the useful effects of the MRAC-based speed controller.**

I. Introduction

The MICROPROCESSOR-BASED digital control technique has become indispensable with the growing requirements for much higher supervising capability and far better control performance in the motor control systems. It has, for example, largely contributed to provide them with the powerful reliability, availability, and serviceability (RAS) functions [1]. It can also contribute to the practical application of the advanced control techniques such as the ones based on the modern control theory. This trend is found not only in the new application in the rising industries such as robot, factory automation, and so forth, but also in the replacement of plants in the established industries [2].

Model reference adaptive control is a class of adaptive controls and belongs to the modern control theory. In the model reference adaptive system, a reference model specifies the desired control performance and a control input is generated to drive the controlled system to track the response of the reference model.

Various adaptive control algorithms have been proposed. Unfortunately, however, they are rather complicated and only a few examples of the practical applications of MRAC have been reported in the process control, autonavigation systems, etc. [3], [4], where the large or minicomputers are available. In motor drives the use of the large or minicomputers as controllers is not realistic, and microprocessors are used instead. The complexity in the algorithm is quite a large obstacle to microprocessors. Almost all applications of the adaptive control to motor drives still remain in computer simulation study for this reason.

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The authors have already applied the control technique to the current control of the thyristor Leonard system [5] and succeeded in speedup of the current response in the discontinuous current mode. The effect was demonstrated by experiment.

In this paper, MRAC is applied to the speed control of the thyristor Leonard system. The algorithm of MRAC is based on the linear model following control (LMFC) and is the combination of the adaptive controller with LMFC. This adaptive algorithm is outlined first. The microprocessor-based experimental setup is constructed and its configuration is overviewed. The experimental results follow and they demonstrate the remarkable effects of MRAC over the parameter perturbation in the controlled system and load disturbance.

II. MRAC Algorithm Based on LMFC

A. Preparation

The motor drive system is generally a second or higher order system; it has at least two dynamics in electrical and mechanical responses. The first-order MRAC algorithm is, however, realistic for the capability of the microprocessors available on the market at present.

The MRAC-based speed controller in this paper has a current controller as its minor loop. The control logic of the current controller is proportional-integral (PI) and the P- and I-gains are so determined as to make the rise time of the current response shorter than that obtained by the conventional PI-controller design practice. The shorter rise time means the faster termination of the transient at every control period. The current minor loop, regulated the way mentioned above, can be regarded as a variable-gain component with a value that fluctuates around unity as illustrated in Fig. 1 if thus regulated current response is much faster than the prescribed speed response. The current minor loop has an effect to eliminate the influence of the back electromotive force (E_B) as well.

The design technique reduces the transfer function between the current reference (I_{REF}) and the rotor speed (N) to the first-order one as shown in Fig. 2. The first-order MRAC thus becomes applicable to the dc motor speed control.

B. Derivation of MRAC Algorithm

The MRAC algorithm in this paper is based on LMFC and can be referred to as adaptive model following control (AMFC) as well.

Fig. 3 explains the construction of a typical LMFC which the MRAC algorithm is based on. Fig. 3(a) and 3(b) are the

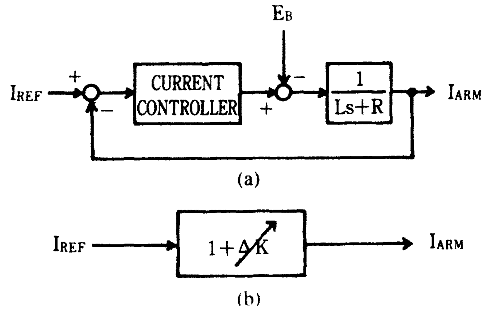

Fig. 1. Effect of current controller. (a) Current control minor loop. (b) Equivalent block.

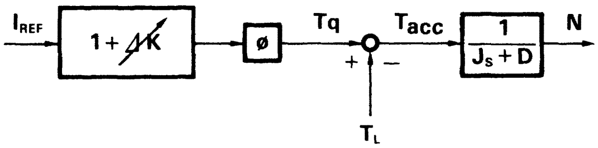

Fig. 2. Approximated electromechanical dynamics.

block diagrams of the first-order controller system and the first-order reference model in time-discrete form, respectively. The p, q, p_M, and q_M are defined as follows.

$$p = \exp\left(-T_c/T_s\right) \tag{1}$$

$$q = K(1-p) \qquad (K: \text{gain}) \tag{2}$$

$$p_M = \exp\left(-T_{cM}/T_s\right) \tag{3}$$

$$q_M = K_M(1-p_M) \qquad (K_M: \text{gain}) \tag{4}$$

where T_c and T_{cM} are the time constants of the controlled system and the reference model, respectively, and the T_s is the sampling period. The objective of LMFC is to make the response of the controlled system follow that of the reference model. The compensation gains placed in front of the controlled system, as in Fig. 3(c), serve the above objective. A closer look at Fig. 3(c) indicates that it is identical to Fig. 3(b). The identicalness between them guarantees the model-following capability of the LMFC.

In the application of the adaptive control system the controlled system parameters p and q are supposed to be unknown and/or variable and they are denoted by $p(k)$ and $q(k)$ as in Fig. 4(a). Accordingly the compensation gains can no longer be constant either. They should be adjusted during operation through the estimation of $p(k)$ and $q(k)$:

$$G_F(k) = \frac{q_M}{q(k)} \tag{5}$$

$$G_B(k) = \frac{p_M - p(k)}{q(k)}. \tag{6}$$

The adaptation mechanism takes care of the estimation as illustrated in Fig. 4(b). The correct and quick estimation of $p(k)$ and $q(k)$ can reduce Fig. 4(b) to Fig. 3(b) and realize the following adaptive model.

The estimation algorithm is based on the general theory of

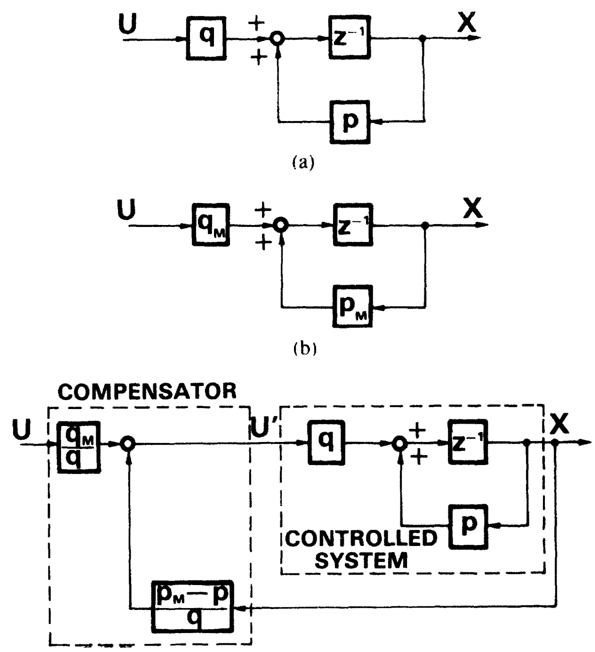

Fig. 3. Derivation of typical LMFC. (a) Controlled system. (b) Reference model. (c) Model-following system.

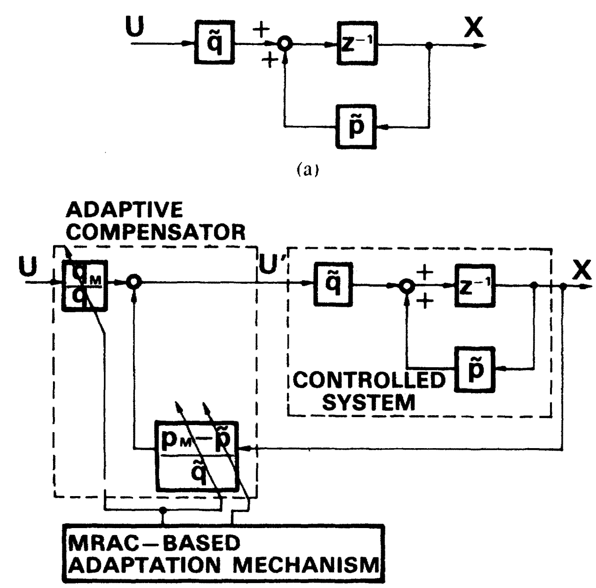

Fig. 4. Fundamental structure of MRAC-based control system. (a) Controlled system. (b) Adaptive model-following system.

MRAC [6], [7], [8] and is given as

$$p(k+1) = p(k) + K_p x(k) e^*(k+1) \tag{7}$$

$$q(k+1) = q(k) + K_q U'(k) e^*(k+1) \tag{8}$$

where $e^*(k)$ is the adaptive error signal and is defined as

$$e^*(k+1) = \frac{p_M e^*(k) + x(k+1) - [p(k)x(k) + q(k)U'(k)]}{1 + K_p x^2(k) + K_q U'^2(k)}. \tag{9}$$

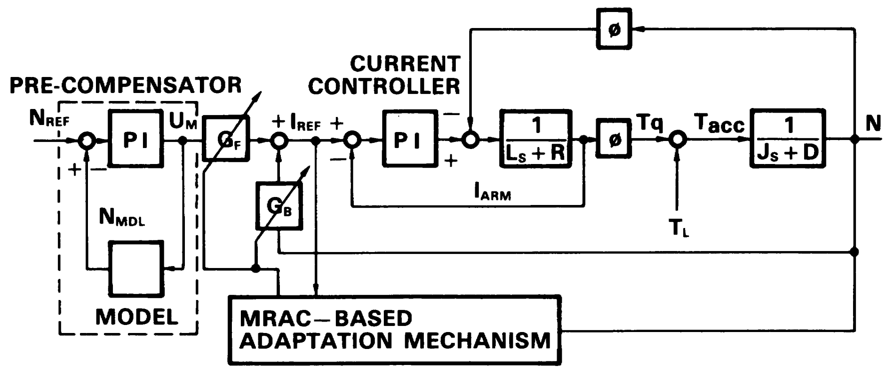

Fig. 5. Block diagram of MRAC-based speed controller.

The input reference signal to the controlled system $U(k)$ is then generated as

$$U(k)=\frac{[p_M-p(k+1)]x(k+1)+q_M U(k+1)}{q(k+1)}. \quad (10)$$

The mathematical description is detailed in Appendix.

C. MRAC-Based Speed Controller

The basic structure of the MRAC system presented in Fig. 4(b) is directly applied to the dc-motor speed-control system as shown in Fig. 5. The U and U' in Fig. 4(b) correspond to U_M and I_{REF} in Fig. 5, respectively. The precompensator is placed in front of the U_M for higher control performance [8].

III. Overview of Experimental Setup

Fig. 6 presents the configuration of experimental setup of the microprocessor-based adjustable-speed dc-motor drive system. The main CPU is a 16-bit microprocessor. The electrically programmable read-only memory (EPROM) of 8 kbytes and random access (RAM) of 20 kbytes are equipped; 4 kbytes are assigned to the program monitor and another 4 kbytes are used for the control program out of the total 28 kbytes. The main CPU takes care of all the required tasks except the triggering control of the thyristors in the four-quadrant naturally commutated dual converter. The triggering control is based on phase-locked loop (PLL) technique, and an 8-bit single-packaged microcomputer performs this task. The armature current is picked up by a current sensor and fed back to the main CPU as an average value over the period of 60° electric angle (3.33 msec) through the combination of a voltage/frequency (V/F) converter and a counter. The synchroresolver detects the rotor position with the resolution of 16 bits per rotation. The detected signal is fed to the main CPU through the resolver/digital (R/D) converter. The main CPU assesses the average rotor speed over the period of 4 msec. The self-controlled synchronous motor is coupled with the dc motor and serves as a load torque generator. This motor is governed by its own microprocessor-based controller, the details of which are not shown in this figure. Table I lists the constants of the dc motor plus the load.

As mentioned above, the 16-bit main CPU serves as a master processor and the 8-bit microcomputer as a slave controller. This sharing of tasks brings enough time allowance to the main CPU to perform the calculation for the adaptive control.

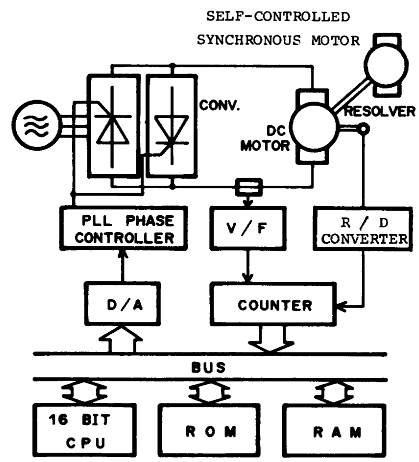

Fig. 6. Configuration of experimental setup.

TABLE I
SYSTEM PARAMETERS

Rated power	36 kW
Rated voltage	220 V
Rated current	183 A
Rated speed	3600 r/min
ϕ	0.533 V·sec/rad
J	0.5 N·m·sec²/rad
D	0.25 N·m·sec/rad
L	8.5 mH
R	0.2 Ω
T_s (speed)	10.0 msec
T_s (current)	3.33 msec

The dual sampling system is employed in this system. The current control (PI control) is performed every 3.33 msec, and the speed control (adaptive control) every 10 msec.

IV. Experimental Results

A. Effect on Change in System Parameters

Fig. 7(a) presents the basic acceleration performance of the dc motor controlled by the MRAC-based speed controller. The actual rotor speed N tracked well the reference model speed N_{MDL}, and it has been confirmed that the model-following was realized. The settling time of about 100 msec was obtained.

In Fig. 7(b) the field current I_f was reduced to one-third.

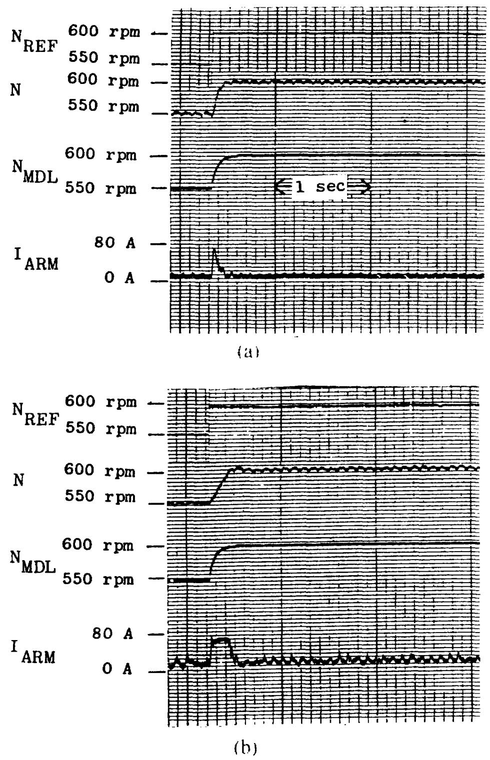

Fig. 7. Effect of MRAC-based speed controller over change in field current. (a) $I_f = 2.4$ A. (b) $I_f = 0.8$ A.

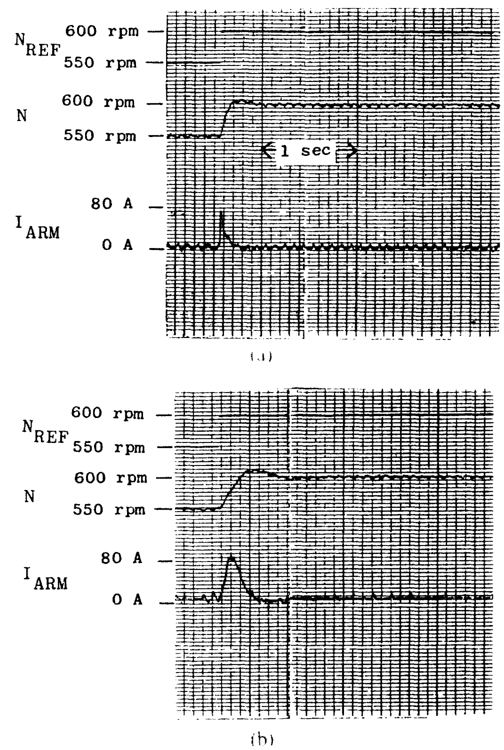

Fig. 8. Deterioration in speed response controlled by PI speed controller due to change in field current. (a) $I_f = 2.4$ A. (b) $I_f = 0.8$ A.

The reduction in the field current is approximately equivalent to the increase in the mechanical inertia J, as explained below, if the mechanical friction loss can be neglected. (11) gives the mechanical transfer function $G_M(s)$

$$G_M(s) = \frac{\phi}{Js + D} \tag{11}$$

where ϕ is the torque coefficient and is proportional to the field current. If the mechanical friction loss is negligible, (11) becomes

$$G_M(s) = \frac{\phi}{Js}. \tag{12}$$

Thus the reduction in the field current can be regarded as the increase in the mechanical inertia. In Fig. 7(b), because the current limiter was active at 80 A the settling time of about 200 msec was obtained. Fig. 8 shows the experimental results by the conventional PI speed controller in the same condition as in Fig. 7, for comparison. The parameters of the PI controller were so adjusted as to obtain nearly the same rotor speed response in Fig. 8(a) as in Fig. 7(a). The field current was reduced to one-third again in Fig. 8(b). A large overshoot appeared and the settling time was prolonged, to about 650 msec in this case. Comparison between these two sets of responses concludes that the MRAC-based speed controller has the adaptive compensation effect on the parameter change in the controlled system.

B. Effect on Load Torque Disturbance

The variation in load torque T_L is present in almost any system. In a steel-rolling mill, for example, when an iron ingot is intruded into it, the impact of the load torque is applied to the motor. The load-torque impact causes a decrease in rotor speed, which is the so-called impact drop. Fig. 9 presents an example of the rotor-speed deviation from the constant speed reference of 1000 r/min due to the load-torque disturbance, where the speed control logic was the PI control and its parameters setting was the same as in Fig. 8(a). The load torque was generated by the self-controlled synchronous motor as mentioned in Fig. 6. The recovery time of the rotor speed N to the speed reference of 1000 r/min was about 450 msec in both applying and releasing the load-torque.

The load-torque disturbance can be treated as a variation in the torque coefficient ϕ as illustrated in Fig. 10. Although the torque coefficient ϕ is usually defined as the ratio of the motor torque T_q to the armature current I_{ARM}, it can include the load torque T_L in it as its fluctuation if it is interpreted as the ratio of the acceleration torque T_{acc} to I_{ARM}. The MRAC-based speed controller can therefore compensate the rotor-speed deviation due to the load-torque disturbance such as impact drop. Fig. 11 demonstrates the effect of the MRAC-based speed controller on the load torque disturbance. In this experiment the same load torque was applied and released as in Fig. 9. It is observed in Fig. 11 that the recovery time of the rotor speed is about 150 msec which is one-third that obtained by the conventional PI-control speed controller as shown in Fig. 9. The MRAC-based speed controller in this paper thus has the powerful effect, even on a sudden change in load-torque disturbance.

V. Conclusion

The model-reference adaptive control has been successfully applied to the microprocessor-based adjustable-speed dc-motor drive system. Experimental results have demonstrated

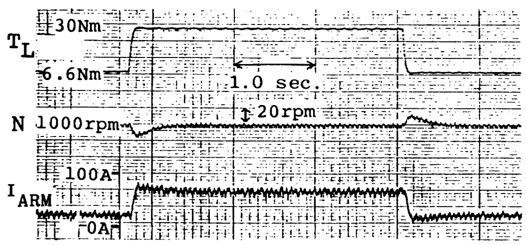

Fig. 9. Rotor speed deviation due to load torque impact (PI control).

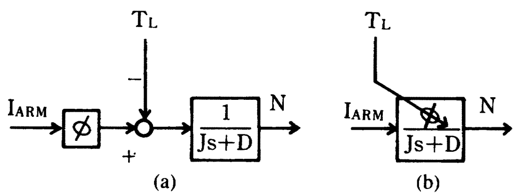

Fig. 10. Equivalent interpretation of load torque disturbance. (a) Load torque input. (b) Equivalent block.

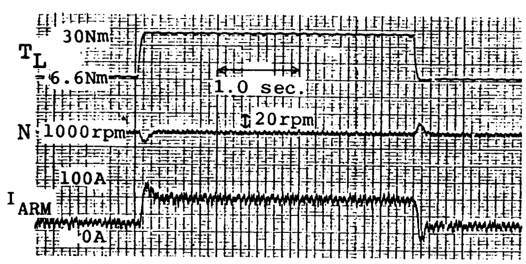

Fig. 11. Rotor speed deviation due to load torque.

that the MRAC-based speed controller has powerful effects to maintain the prescribed control performance in the presence of the parameter perturbation and load-torque disturbance in the controlled system. Further study will be focused on the simplification of the MRAC algorithm, the development of the higher order MRAC-based controller, and so forth.

Appendix

The first-order controlled system (dc motor or plant) is described as

$$x(k+1) = px(k) + qU'(k) \tag{13}$$

where the plant delay is assumed to be one sampling period and $U(k)$ and $x(k)$ are the input and output, respectively. The reference model is given by

$$x_M(k+1) = p_M x_M(k) + q_M U(k) \tag{14}$$

where $U_M(k)$ and $x_M(k)$ are the reference model input and output, respectively. The plant-model error $e(k)$ is defined as

$$e(k) = x(k) - x_M(k). \tag{15}$$

The objective of the adaptive control is to generate the plant input $U(k)$, which reduces the plant-model error to zero as k goes to infinity. The above equations yield

$$e(k+1) = p_M e(k) + (p - p_M)x(k) + qU(k) - q_M U(k). \tag{16}$$

If the underlined terms of (16) can be made to be zero, the (16) becomes

$$e(k+1) = p_M e(k). \tag{17}$$

The p_M must be chosen as

$$|p_M| < 1 \tag{18}$$

and then

$$\lim_{k\to\infty} e(k) = 0. \tag{19}$$

The plant input $U(k)$ therefore should be

$$U(k+1) = \frac{(p_M - p)x(k+1) + q_M U(k+1)}{q}. \tag{20}$$

Since the plant parameters p and q are, however, unknown, they are replaced with their respective predicted quantities $p(k)$ and $q(k)$, and (20) is rewritten as

$$\begin{aligned} U(k+1) &= \frac{[p_M - p(k+1)]x(k+1) + q_M U(k+1)}{q(k+1)} \\ &= \frac{p_M - p(k+1)}{q(k+1)} x(k+1) + \frac{q_M}{q(k+1)} U(k+1) \\ &= G_F(k+1)x(k+1) + G_B(k+1)U(k+1). \end{aligned} \tag{21}$$

From the above equations the plant and model equations are redefined as

$$x(k+1) = px(k) + qU(k) \tag{22}$$

$$x_M(k+1) = -p_M e(k) + p(k)x(k) + q(k)U(k). \tag{23}$$

Then

$$e(k+1) = p_M e(k) + \{p - p(k)\}x(k) + \{q - q(k)\}U'(k). \tag{24}$$

Since the general MRAC theory based on Popov's hyperstability theorem [6], [7] cannot be applied directly to the plant-model error expression given by (24), auxiliary error signal $e_a(k+1)$ is introduced

$$\begin{aligned} e_a(k+1) = {} & p_M e_a(k) + \{p(k) - p(k+1)\}x(k) \\ & + \{q(k) - q(k+1)\}U'(k). \end{aligned} \tag{25}$$

The adaptive error signal $e^*(k)$ is then given by

$$\begin{aligned} e^*(k) &= e(k) + e_a(k) \\ &= G(z)\{p - p(k+1)\}x(k) + \{q - q(k+1)\}U'(k). \end{aligned} \tag{26}$$

In (26) the pulse transfer function $G(z)$

$$G(z) = \frac{z}{z - p_M} \tag{27}$$

is apparently strictly positive real, so that the well-known adaptive algorithm of the "integration of product" can be used to predict the $p(k)$ and $q(k)$ [6], [7]

$$p(k+1)=p(k)+K_p x(k) e^*(k+1) \tag{28}$$

$$q(k+1)=q(k)+K_q U'(k) e^*(k+1). \tag{29}$$

According to the general theory of MRAC, the above adaptive algorithm ensures both

$$\lim_{k\to\infty} e^*(k)=0 \tag{30}$$

and

$$\lim_{k\to\infty} e(k)=0. \tag{31}$$

The objective of adaptive control is thus satisfied.

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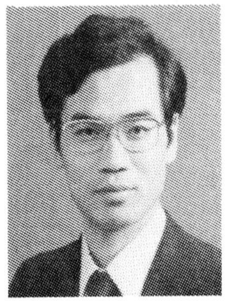

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