Microprocessor-Controlled DC Motor for Load-Insensitive Position Servo System

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Abstract—The conventional proportional P controller has been often used as the position controller of the dc servo motor. When the unknown and inaccessible load torque, such as the coulomb friction, the gravity, and so on, is imposed on the dc servo motor, this control system has the steady- and/or transient-state error.

This error will be reduced by a new method in the paper, which is based on the observer theory and programmed in the microprocessor. The deadbeat observer in this paper can estimate the sum of all the external forces quickly with a very simple structure. The new torque regulator based on this observer is expected to realize no steady-state-error and little transient-state-error position control even in employing only the P controller, whether various types of external force are imposed or not. Moreover, according to the observer theory, this system has merit in that this response to the external force can be determined independently of the response to the position reference. Numerical and experimental results are also shown.

Nomenclature

L	Armature inductance.
R	Armature resistance.
J	Total inertia.
T_{load}	External force.
e_a	Armature voltage.
Θ	Rotor position.
η	State variable in the observer.
S	Laplace operator.
α, β	Two poles, respectively, in the complex domain.
K_t	Torque constant.
K_e	Back EMF constant.
I_a	Armature current.
I_f	Field current.
ω_r	Motor speed.
Θ^{ref}	Rotor position reference.
$\hat{T}_{load}$	Estimated external force.
Z^{-1}	One-step delay operator.

I. Introduction

RECENTLY, microprocessor control systems have become requisite because of their high performance with economical hardware and software. In servo applications, the modern digital control can satisfy the various engineering specifications [1], [2]. In other words, the modern digital control has the large potentiality to improve the system performance.

Generally, the position controller of the dc servo motor is requested to have a rapid and accurate response for the position reference whether the external force is imposed or not. For example, for the robotics applications, the conventional P controller has often been used as the position controller. The suitable pole and zero assignments are easily realizable by this P controller, however, it has the steady- and/or transient-state error according to the external force. Therefore, the control algorithm should include the complicated calculation process to eliminate the error according to *a priori* known external forces which are, for example, the gravitational force and the force interactions among joints [3]. However, as the result, the control system may occupy the long process in the microprocessor system and cannot regulate the rotor position in a desirable sampling time.

This problem may be overcome by a proposed method in the paper, which is based on the discrete observer theory and realized in the microprocessor. It is desirable to adopt the quick and simple external force compensation. In the dc motor, since the external force can be defined as the uncontrollable but observable state variable, the deadbeat observer, to estimate the sum of the external forces, is constructed with a simple algorithm. Accordingly, using the feedforward torque regulator based on this observer, the quick output torque response and the small fluctuation of the rotor position can become realized. Besides, since this torque regulator is independent of the position controller, employing the conventional technique to design the position controller is possible [4], [5]. The discrete observer should be employed because this type of observer can estimate the external force simply and quickly.

Experimental and numerical examples based on a 0.8-kW dc servo motor show that the proposed method is effective for good position control.

II. Estimation of External Force

The impact of external force to the dc servo motor gives rise to the steady- and/or transient-state error when the position control system is designed by conventional controllers. However, if the value of the external force is accurately detected or estimated, the feedforward torque regulator, which can rapidly cancel out this offset, is possible. The indirect method to estimate the external force is considered to be practical and economical. In this paper, this estimation is made by the

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discrete observer. The observer is constructed on the basis of the state equation.

The dc servo motor is represented simply as shown in Fig. 1. Here, the following discrete state equation holds:

$$X(k+1)=AX(k)+bu(k)+dT_{\text{load}}(k) \tag{1}$$

where

$$X(k)=\begin{pmatrix}\omega_r(k)\\ I_a(k)\\ \Theta(k)\end{pmatrix}$$

$$A=\begin{pmatrix}a_1 & a_2 & 0\\ a_3 & a_4 & 0\\ a_7 & a_8 & 1\end{pmatrix}$$

$$b=\begin{pmatrix}b_1\\ b_2\\ b_3\end{pmatrix}$$

$$d=\begin{pmatrix}d_1\\ d_2\\ d_3\end{pmatrix} \tag{2}$$

$$u(k)=e_a(k).$$

Here

$$a_1=\frac{R+L\alpha}{LM}e^{\alpha T}+\frac{R+L\beta}{LN}e^{\beta T}$$

$$a_2=\frac{Kt}{JM}e^{\alpha T}+\frac{Kt}{JN}e^{\beta T}$$

$$a_3=\frac{Ke}{LN}e^{\alpha T}+\frac{Ke}{LM}e^{\beta T}$$

$$a_4=\frac{\alpha}{M}e^{\alpha T}+\frac{\beta}{N}e^{\beta T}$$

$$a_7=\frac{R}{L\alpha\beta}+\frac{L\alpha+R}{L\alpha M}e^{\alpha T}+\frac{L\beta+R}{J\beta N}e^{\beta T}$$

$$a_8=\frac{Kt}{J\alpha\beta}+\frac{Kt}{J\alpha M}e^{\alpha T}+\frac{Kt}{J\beta N}e^{\beta T}$$

$$b_1=\frac{Kt}{LJ\alpha M}(e^{\alpha T}-1)+\frac{Kt}{LJ\beta N}(e^{\beta T}-1) \tag{3}$$

$$b_2=\frac{1}{LM}(e^{\alpha T}-1)+\frac{1}{LN}(e^{\beta T}-1)$$

$$b_3=\frac{KtT}{LJ\alpha\beta}+\frac{Kt}{LJ\alpha^2 M}(e^{\alpha T}-1)+\frac{Kt}{LJ\beta^2 N}(e^{\beta T}-1)$$

$$d_1=\frac{L\alpha+R}{LJ\alpha N}(e^{\alpha T}-1)+\frac{L\beta+R}{LJ\beta M}(e^{\beta T}-1)$$

$$d_2=\frac{Ke}{LJ\alpha M}(e^{\alpha T}-1)+\frac{Ke}{LJ\beta N}(e^{\beta T}-1)$$

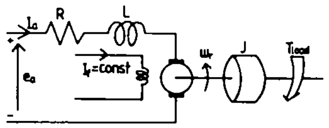

Fig. 1. Simplified plant model of dc motor.

$$d_3=\frac{-RT}{LJ\alpha\beta}+\frac{L\alpha+R}{LJ\alpha^2 N}(e^{\alpha T}-1)+\frac{L\beta+R}{LJ\beta^2 M}(e^{\beta T}-1)$$

$$M=\alpha-\beta,\quad N=\beta-\alpha.$$

T is a sampling time. Both α and β are the open-loop poles of the dc servo motor, and are led by the following characteristic equation:

$$S\left\{S\left(S+\frac{R}{L}\right)+\frac{K_eK_t}{LJ}\right\}=S(S-\alpha)(S-\beta) \tag{4}$$

where S is the Laplace operator.

In (1), the external force T_{load} is an unknown and inaccessible input. Therefore the observer is considered to be suitable to estimate this unknown input T_{load}. Generally, as T_{load} is assumed to be a step-like variable, it can be represented by the following linear difference equation [6]:

$$T_{\text{load}}(k+1)=T_{\text{load}}(k). \tag{5}$$

Equation (5) is an approximate equation. However, this approximation is effective in simplifying both the controller and the observer, because this approximation results in only at least one sampling delay in the estimation of T_{load} and has no influence on the magnitude of the estimated value of T_{load}. If (5) is represented as the higher order difference equation, that brings the better approximation of T_{load}. As a result, however, more sampling delay is necessary to estimate T_{load} in the observer. Because practically the minimum-order approximation of T_{load} gives the fastest estimation, (5) is adopted in this paper. Adding this difference equation (5) to the state equation (1), the external force T_{load} is transformed from the unknown and inaccessible input to the observable state variable in the state representation. The total system can be written in the augmented difference equations as follows:

$$\begin{pmatrix}T_{\text{load}}(k+1)\\ \omega_r(k+1)\\ I_a(k+1)\\ \Theta(k+1)\end{pmatrix}=\begin{pmatrix}1 & 0 & 0 & 0\\ a_5 & a_1 & a_2 & 0\\ a_6 & a_3 & a_4 & 0\\ a_9 & a_7 & a_8 & 0\end{pmatrix}\begin{pmatrix}T_{\text{load}}(k)\\ \omega_r(k)\\ I_a(k)\\ \Theta(k)\end{pmatrix}+\begin{pmatrix}0\\ b_1\\ b_2\\ b_3\end{pmatrix}e_a(k) \tag{6}$$

$$y(k)=\begin{pmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}\begin{pmatrix}T_{\text{load}}(k)\\ \omega_r(k)\\ I_a(k)\\ \Theta(k)\end{pmatrix} \tag{7}$$

where

$$a_5=-\frac{R}{JL\alpha\beta}+\frac{R+L\alpha}{LJ\alpha N}e^{\alpha T}+\frac{R+L\beta}{LJ\beta M}e^{\beta T}$$

$$a_6=\frac{Ke}{LJ\alpha\beta}+\frac{Ke}{LJ\alpha M}e^{\alpha T}+\frac{Ke}{LJ\beta N}e^{\beta T} \tag{8}$$

$$a_9=-\frac{1}{J\alpha\beta}-\frac{1}{J\alpha M}e^{\alpha T}-\frac{1}{J\beta N}e^{\beta T}.$$

Since the augmented system in (6) and (7) is completely observable, the minimum-order discrete observer which estimates T_{load} can be completed as follows [7]:

$$\eta(k+1)=f\eta(k)+(m\quad g)\begin{pmatrix}\omega_r(k)\\ I_a(k)\end{pmatrix}+he_a(k) \tag{9}$$

$$\hat{T}_{load}(k)=\eta(k)-\lambda\omega_r(k) \tag{10}$$

where

$$f=1+\lambda a_5$$
$$m=\lambda(a_1-1-\lambda a_5)$$
$$g=\lambda a_5$$
$$h=\lambda b_1. \tag{11}$$

$\hat{T}_{load}$ is the estimated value of the external force T_{load}. η is a state variable in this observer and is required in the mathematical process. The proposed observer is a so-called reduced one [7], which does not require Θ as one of the inputs of the observer, because this observer can gather all the information of rotor acceleration from the detected value of motor speed ω_r. This observer can estimate the sum of all the imposed external forces at the same time. The pole assignment of this observer is determined arbitrarily by selecting the constant λ. In this paper, the minimum-order deadbeat observer whose pole is on the origin in Z plane is adopted. The schematic block diagram of the observer is shown in Fig. 2.

In the steady state, the transfer function of this observer is shown as

$$\lim_{z\to 1}\frac{Z-1}{Z}\frac{\hat{T}_{load}(k)}{T_{load}(k)}=\frac{K_t^*}{K_t}. \tag{12}$$

K_t^* is the nominal value of torque constant K_t. Therefore, the observer can estimate T_{load} without steady-state error only if the torque constant K_t (i.e., the back EMF constant K_e) is fixed.

III. Design of Position Controller

When the position controller is designed, both the rise time and overshoot are often taken up as its transient performance index, since the pole assignment defines mainly the loci of all state variables from the initial state to the new equilibrium point. Here, only the control poles of the dc servo motor are worth being taken into account in the design of the position controller, because the position controller is independent of

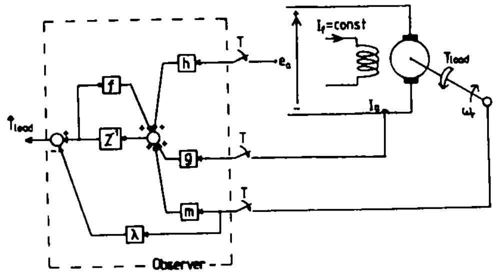

Fig. 2. Schematic block diagram of realized observer.

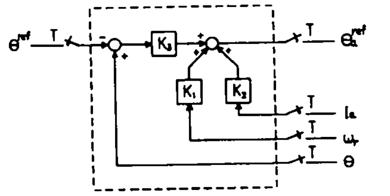

Fig. 3. Schematic block diagram of position controller.

the deadbeat observer from the viewpoint of pole allocations when the parameters are well matched.

In this paper, the position controller based on the P control is designed for the dc servo motor of (1) as follows [8]. The original characteristic equation of the plant system is shown in (13), and the desired closed-loop characteristic equation is shown in (14). For the desired pole assignment in (14), the following state gain vector is introduced as (16). These constants of feedback gain, K_1, K_2, and K_3 in (16), can be conducted from the matrix equation (15) using (13) and (14). The schematic block diagram of the position controller is shown in Fig. 3.

$$\det|ZI-A|=Z^3+\zeta_2Z^2+\zeta_1Z+\zeta_0 \tag{13}$$

$$\det|ZI-A-bK|=Z^3+\gamma_2Z^2+\gamma_1Z+\gamma_0 \tag{14}$$

$$K=(\zeta_2-\gamma_2,\ \zeta_1-\gamma_1,\ \zeta_0-\gamma_0)\begin{pmatrix}1&\zeta_2&\zeta_1\\0&1&\zeta_2\\0&0&1\end{pmatrix}^{-1}\cdot[b\quad Ab\quad A^2b]^{-1} \tag{15}$$

$$u(k)=KX(k)=[K_1K_2K_3]X(k). \tag{16}$$

In the steady state, each transfer function of this position controller is shown in (17) and (18). In (17), this position controller has no steady-state error even if the system parameters are varied. However, in (18), this position controller has a steady-state error besides a transient error when the external force T_{load} is imposed.

$$\lim_{z\to i}\frac{Z-1}{Z}\frac{\Theta(Z)}{\Theta^{ref}(Z)}=\frac{K_3K_t}{K_3K_t}. \tag{17}$$

$$\lim_{z\to 1}\frac{Z-1}{Z}\frac{\Theta(Z)}{T_{load}(Z)}=\frac{-(R+K_2)}{K_3K_t}. \tag{18}$$

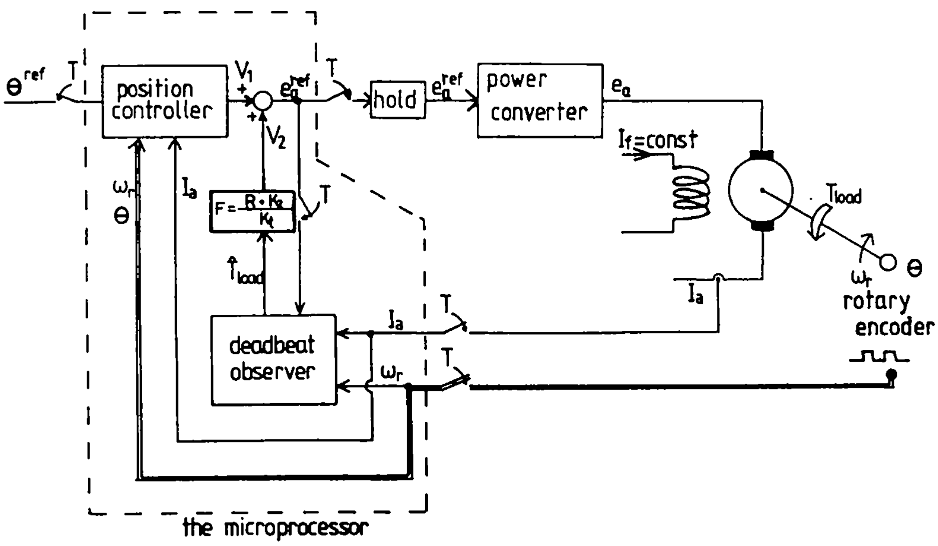

Fig. 4. Total position control system using the controlled voltage source.

IV. Load-Insensitive Position System

In order to suppress the position error according to the external force T_{load}, it is effective to use the torque regulator which bypasses the position controller. Estimation by the observer gives no influence to the torque-position control, therefore it conducts the decoupling of both the position controller and the torque regulator. These characteristics are desirable for the total control design. Coupling Fig. 2 with Fig. 3, the total schematic position control system is as shown in Fig. 4. In this paper, the ideal voltage source whose gain is unity is assumed as a power converter. Therefore, as the voltage command e_a^{ref} is completely equal to the armature voltage e_a, the realized observer can employ the value of e_a^{ref} instead of the actual value of e_a. In the case in which the controlled current source is adopted, the proposed method is also applicable with a few modifications as described in the next paragraph.

In Fig. 4, the voltage command V_2 which determines the armature current I_a corresponding to the estimated external force T_{load} is added to the output V_1 of the position controller. The feedforward gain F of the torque regulator is defined in (19), because the torque regulator ought to counterbalance the external force T_{load} by the armature voltage e_a [9]. The transfer gain from the armature voltage e_a to the generated torque is $K_t/(R + K_2)$, where the armature inductance L is ignored. Therefore the external force T_{load} is cancelled out when the armature voltage e_a is equal to $\{T_{load} \times ((R + K_2)/K_t) + V_{acc}\}$, where V_{acc} is the voltage V_1 corresponding to the acceleration torque in Fig. 4. When T_{load} in the above equation is replaced with $\hat{T}_{load}$, the following equation is derived. This equation is represented in Fig. 4.

$$F=\frac{R+K_2}{K_t} \tag{19}$$

$$T_{load}\,\frac{R+K_2}{K_t}+V_{acc}=V_2+V_1. \tag{20}$$

R^* is the nominal value of armature resistance R. The output of the torque regulator is represented as (21). Substituting the result of (12) into (21), the output of torque regulator in steady state is represented as (22).

$$v_2(k)=\frac{R^*+K_2}{K_t^*}\,\hat{T}_{load}(K). \tag{21}$$

$$\lim_{z\to 1}\frac{Z-1}{Z}\cdot v_2(k)=\frac{R^*+K_2}{Kt^*}\cdot\frac{K_t^*}{K_t}\,T_{load}(k)=\frac{R^*+K_2}{Kt}\,T_{load}(k). \tag{22}$$

In (22), the torque regulator has no steady-state error if only the armature resistance R is regarded as constant. For reducing the sensitivity, it is effective to employ the high-current minor loop gain. In such a case, it is also easy to realize the similar system. The only difference is the feedforward gain F in Fig. 4. Therefore, in the case in which the power converter is a controlled current source, the result is as shown in Fig. 5, similar to Fig. 4. Consequently, the total control system is expected to be a little sensitive to the parameter variations. It is interesting that this is attained without inserting a series integral function. Moreover, the desired dynamic recovery of impact drop, due to the various types of external force, is possible by adjusting the feedforward gain F. This recovery process can be regulated independently of the transient process by the position reference change, i.e., the control of both position reference and external force can be determined independently. This strong feature of suppressing external force may realize, for example, the decoupling control of each arm of robot manipulators. It means that the conventional control technique, such as the proportional-integral *PI* controller and so on, can be applied to the position control.

When the proposed total control system is realized, both controller and observer can be programmed in the microprocessor, because these calculations can be carried out rapidly

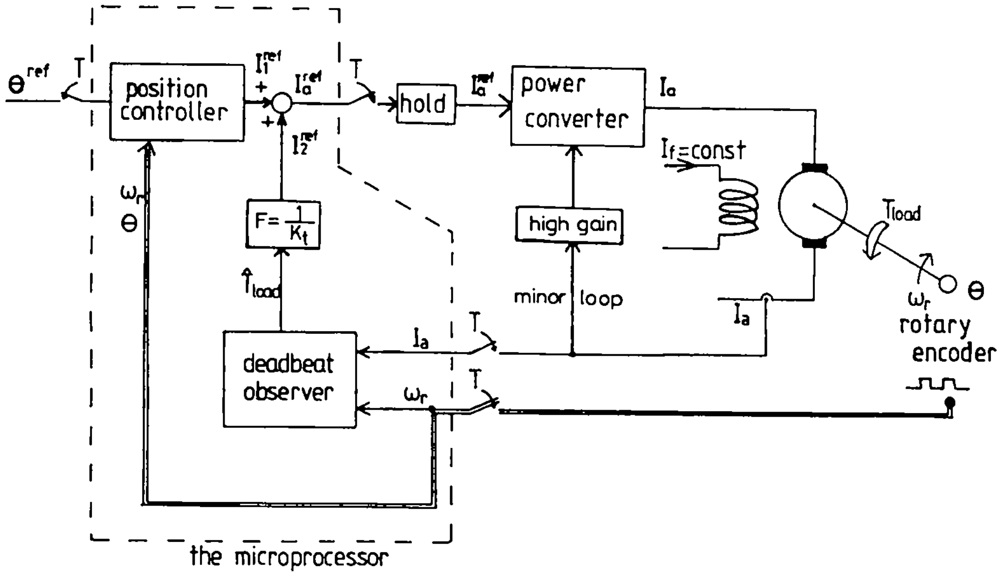

Fig. 5. Total position control system using the controlled current source.

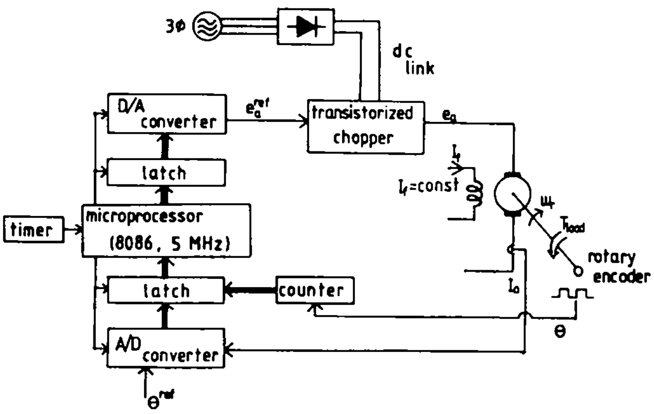

Fig. 6. Schematic diagram of tested motor.

with fine accuracy. In these calculation processes, the system is realized in a 16-bit microprocessor which adopts the floating-point system. As the floating-point system has a wide range of calculation processes, the high fidelity of the sensor signal is assured.

V. Numerical and Experimental Results

The proposed position control system in Fig. 4 is implemented and carried out as shown in Fig. 6. The transistorized chopper is applied as the power converter. The nominal parameters of the dc servo motor are shown in Table I. The constants of the position controller are shown in Table II. The sampling time T is determined as 3 ms. The total position control system is programmed by the assembly language in the 8086 microprocessor, and occupies the 1.5-kbyte memory area.

The experimentally tested system is implemented to make the comparison between the described position control system with the observer and the conventional P controller without the observer.

Fig. 7 shows the response of the rotor position to the change

TABLE I
NOMINAL PARAMETERS OF TESTED DC MOTOR

rated output	0.8 kw	rated speed	1750 rpm
rated current	11 A	L	23.7 mH
R	1.64 Ω	Kt	0.475 N.m./A
Ke	0.475 V.sec/rad	J	2.33 × 10^{-2} Kg.m^2

TABLE II
CONSTANTS OF POSITION CONTROLLER

K_1	-0.943	K_2	0.175
K_3	-9.43		

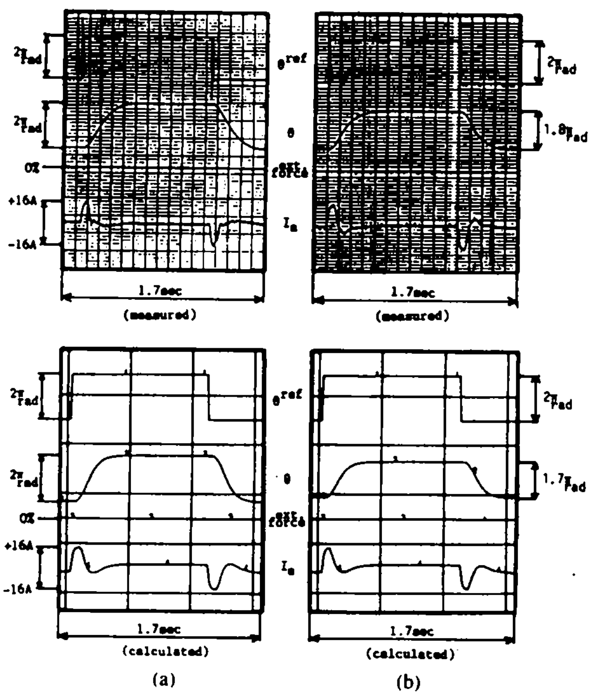

Fig. 7. Experimental and numerical results of the response of the rotor position to the change of position reference: (a) proposed total system; and (b) conventional P controller.

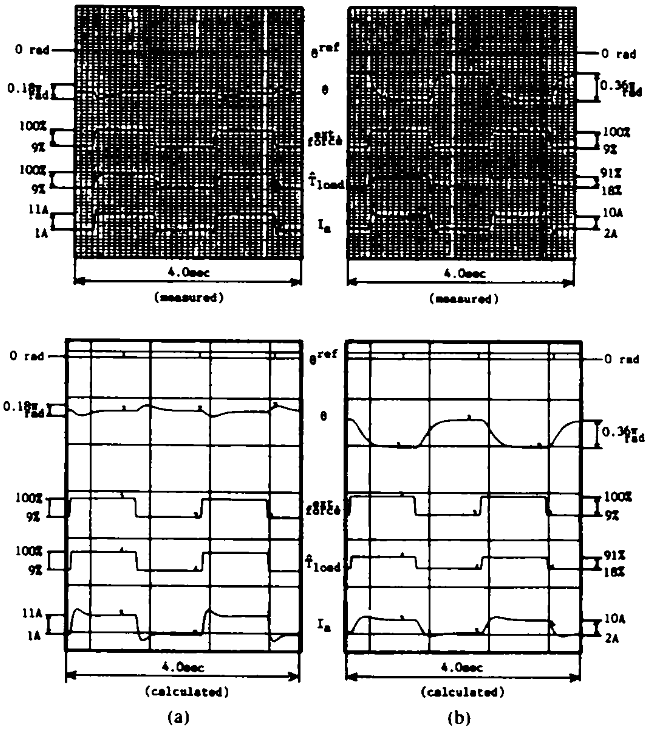

Fig. 8. Experimental and numerical results of the response of the rotor position to the multiple-step external force: (a) proposed total system; and (b) conventional P controller.

of position reference when the external force T_{load} does not exist. Fig. 8 shows the response of the rotor position to the multiple steps of the external force T_{load} imposition when the position reference Θ^{ref} is constant. As a result, the rotor position can be well regulated by the described total system. On the contrary, in the case of the conventional P controller, steady- and transient-state errors according to both the external force and the friction force exist to some extent. The deadbeat observer can well estimate the external force T_{load} as shown in this figure, that shows the new torque regulator to be effective and valid for the torque-position control of the dc servo motor. However, in practice, the armature resistance R varies according to the rising temperature that brings the small steady-state error. This small steady-state error is eliminated by employing an ordinary *PI* speed minor control loop both inside the *P* position controller and outside the observer-based torque control loop. Therefore, when the position servo system is requested to keep the more precise position regulation, the *PI* speed control loop would, preferably, be inserted inside the proposed system.

VI. Conclusion

The described load-insensitive position control system is based on the observer theory. The new torque regulator based on the observer can rapidly cancel out steady- and/or transient-state error position due to the external force which includes various frictions and load torques. Therefore this total system used in the position controller based on the conventional controller is expected to be applied to the various servo systems because of its quick recovery of error position. The total control system can be realized, for example, in the 8086 microprocessor.

Numerical and experimental results show the validity of this position control system.

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