High speed positioning system considering unknown coulomb friction and windup phenomenon

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***Abstract*— In a conventional positioning system, when the position error becomes small, the motor cannot obtain enough deceleration torque. Hence, the position response becomes slow.**

There is also an other positioning system that is to design a position reference from trapezoidal speed reference. This positioning system is valid when load torque and the final goal position are given. However, if the load torque and the final goal vary, its position response cannot have the desired response. In order to overcome these problems, this paper proposes a new high speed positioning system of AC servo motor considering unknown coulomb friction and windup phenomenon. The proposed always uses the maximum acceleration or deceleration torque and the maximum speed.

I. INTRODUCTION

Recently, AC servo motor replaces stepping motor with rapid development of one-chip microcomputer and DSP in the positioning field. In comparison with AC servo motor and stepping motor on condition of the same size, AC servo motor is higher torque and higher efficient than stepping motor.

In the conventional positioning system of AC servo motor, the speed reference is determined by the product of position gain and position error, the speed reference becomes a small value near to the final goal position. Therefore, it is difficult to obtain the sufficient deceleration torque, and its response becomes a slow response.

On the other hand, when the output torque, the inertia moment and the load torque in AC servo motor are known, the optimum speed pattern is determined by these data, and the position reference is given from the speed reference pattern, such as S-shape curve or spline function[1]. In this method, it is possible to carry out the optimum high speed positioning, if to give S-shape curve by the maximum acceleration as a position reference is possible. However, it is necessary for this control method to know the load torque of AC servo motor. However, when the load torque varies, the output response is also changed. Then, it is necessary to form the position reference once more again. In this case, the goal position changes. Moreover, generally the load torque is an unknown variable.

In order to overcome these problems, this paper proposes a new algorithm for high speed positioning system by using the goal position and the coulomb friction load. In this paper, the coulomb friction load torque is estimated by disturbance observer. The effectiveness is confirmed by the numerical simulation results and experimental results[2].

II. CONVENTIONAL POSITIONING SYSTEM

The block diagram of conventional positioning system is shown in Fig.1. The positioning system is P control system and the speed control system is PI control system. Here, θ_m^{ref} is a position reference, θ_m is a motor position, θ_m^{err} is a position error, ω_m^{ref} is a speed reference, ω_m is a motor speed, ω_m^{err} is a speed error, i_q is a torque current and T_L is a disturbance torque. The frequency characteristics of current control system is ordinary enough higher than that of the speed control system. Hence, an output of the speed control system becomes equal to an actual current i_q. In order to carry out the high speed positioning, the position reference θ_m^{ref} of Fig.1 should be a step function.

The tested motor is a surface permanent magnet type synchronous motor, and its specifications are shown in Table I. Fig.2 shows the configuration of experimental system. Each controller of position, speed and current is built in the software servo system by DSP (ADMC401).

TABLE I
SPECIFICATIONS OF TESTED MOTOR

Rated Power	P[W]	90
Rated Voltage	V[V]	100
Flux Interlinkage	Φ_{fa}[Wb]	0.047
Pole Pare	p	5
Rotor Inertia	J[kg·m^2]	6.0×10^{-5}
Armature Resistance	R_a[Ω]	3.08
Armature Inductance	L_a[mH]	8.28
Rated Maximum Speed	ω_{max}[rad/s]	314
Rated Current	i_{max}[A]	$\sqrt{\frac{3}{2}}2$
Rated Voltage	v_{max}[V]	$\sqrt{\frac{3}{2}}70$
Encoder Pulse	[pulse/rev]	2000

The position controller and the speed controller are shown in (1) and (2). The frequency characteristics are shown in Fig.3. Both the sampling time and the cut off frequency of these controllers are shown in Table II. Here, $G_{ry\theta}(s)$ is the reference input response function of position controller, and it is equal to the complementary sensitivity function $T_\theta(s)$. Similarly, $G_{ry\omega}(s)$ is the reference input response function

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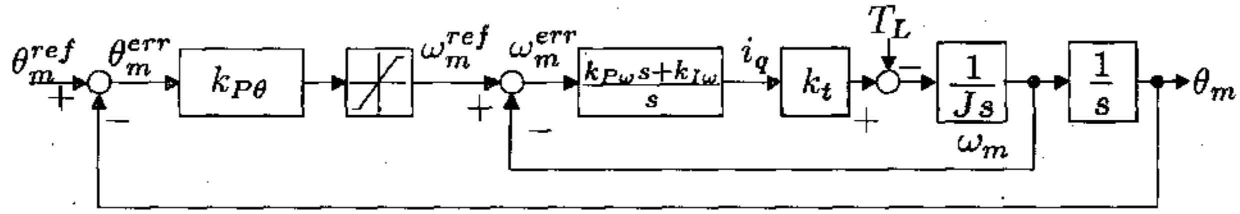

Fig. 1. Block diagram of conventional positioning system

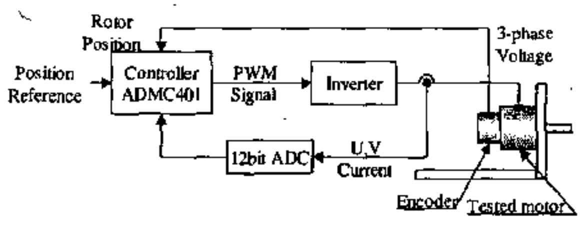

Fig. 2. Configuration of prototype

of speed controller, and it is equal to the complementary sensitivity function $T_\omega(s)$. $S_\theta(s)$ is sensitivity function of position controller. $S_\omega(s)$ is sensitivity function of speed controller.

TABLE II

CHARACTERISTICS OF TESTED SYSTEM

Controller	Position	Speed	Current
Sampling Time	50[μsec]	100[μsec]	1[msec]
Cut off frequency	40[rad/s]	400[rad/s]	4000[rad/s]

$$K_\theta(s) = K_{P\theta} = 40 \tag{1}$$

$$K_\omega(s) = \frac{k_{P\omega}s + k_{I\omega}}{s} = \frac{0.085s + 3.40}{s} \tag{2}$$

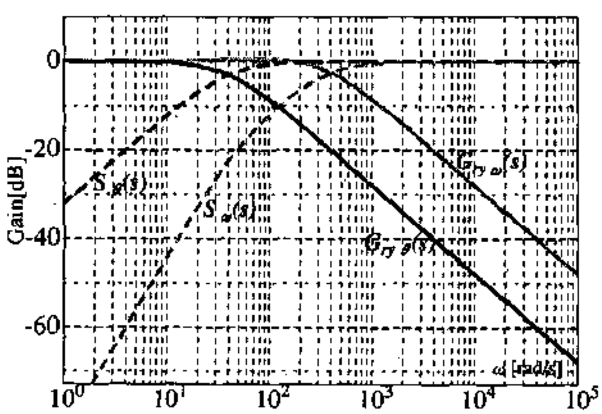

Fig. 3. Frequency characteristics

When the positioning system has a large reference input signal, each servo system of the positioning system has the influence of output saturation. Especially, this output saturation occurs in acceleration mode and deceleration mode[3]-[7]. In this paper, when the output is saturated, as a conventional anti-windup method, the integrator of PI control system is stopped in the control system of Fig.2.

Fig.4 and Fig.5 show the experimental results of the conventional positioning system. In Fig.4 and Fig.5, the position step reference is 6π[rad]. The load condition of Fig.4 is no load torque. The condition of Fig.5 has the coulomb friction as half load torque that is generated by Prony Brake System as shown in Fig.6.

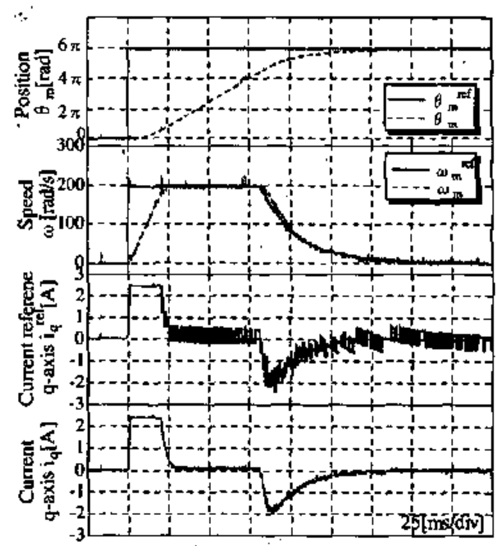

Fig. 4. The experimental results of position step response of using conventional positioning system (without load torque)

In the both results, at the accelerated period, the conventional positioning system is driven by the maximum torque. However, at the deceleration period, it does not use the maximum torque. The position error of deceleration mode is smaller than that of acceleration mode. As the result, the speed reference becomes also small.

III. HIGH SPEED POSITIONING SYSTEM

Fig.7 is an ideal waveform for high speed positioning with a coulomb load torque. In order to carry out the high speed

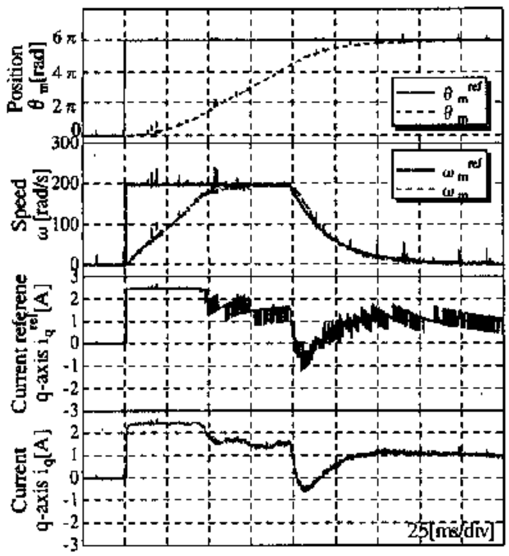

Fig. 5. The experimental results of position step response of using conventional positioning system (with half load torque)

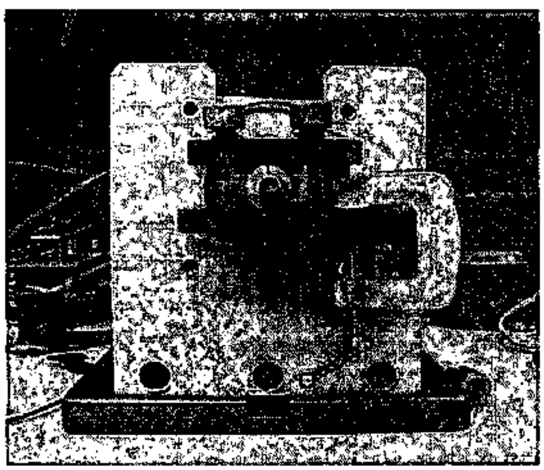

Fig. 6. Prony Brake System

positioning, after the acceleration mode, it is necessary for servo motor to drive at the maximum speed. Finally, a servo motor should decelerate using the maximum torque.

In order to realize these ideal references of motor speed and motor current, this paper proposes a new reference generation algorithm, as shown in Fig.7.

At $[t_0, t_2]$ period in Fig.7, it becomes an ideal response by giving the maximum speed ω_{max} as a speed reference. Next, after the time t_2, the speed reference should be zero. Then, the torque current i_q becomes the maximum deceleration torque $-i_{max}$. However, it is difficult to calculate the time t_2 by the real time algorithm, because t_2 changes by the position reference or an unknown. Accordingly, this paper newly proposes equation (3). The position error, which deserves t_2 is obtained the coulomb friction, which is estimated by the disturbance

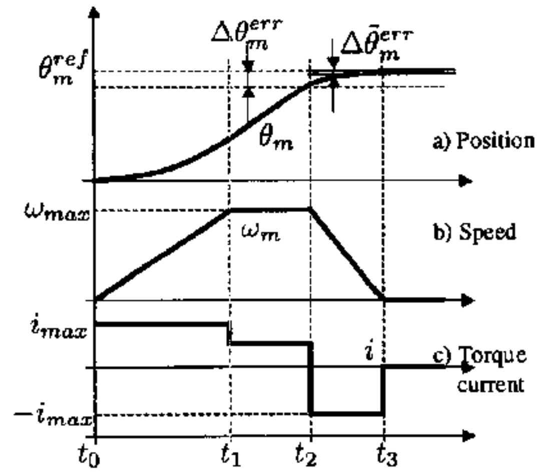

Fig. 7. Ideal waveform of high speed positioning system

observer.

$$\Delta\theta_m^{err} = \frac{\omega_m}{2}\frac{\omega_m}{\frac{k_t}{J}\left(i_{max} + \frac{\hat{T}_L}{k_t}\right)} \tag{3}$$

The block diagram of proposed system is shown in Fig.8. The proposed algorithm calculates $\Delta\theta_m^{err}$ by using (3) in Pre Controller of Fig.8. When the actual position error θ_m^{err} is larger than $\Delta\theta_m^{err}$, the maximum speed ω_{max} is given as a speed reference. At the time t_2, as θ_m^{err} is smaller than $\Delta\theta_m^{err}$, ω_m^{ref} becomes zero. Afterwards, when θ_m^{err} is smaller than $\Delta\tilde{\theta}_m^{err}$ at the time t_3, the positioning control system switches from Pre Controller to the conventional P position control loop. $\Delta\tilde{\theta}_m^{err}$ is defined by trade off of actual positioning response.

This paper prevents the windup phenomenon by using the proposed algorithms[6],[7], in which closed-loop characteristics of servo system does not change. The proposed anti-windup algorithm is a digital nonlinear algorithm. The discrete state space equations of PI controller are shown in (4),(5).

$$x(k+1) = ax(k) + bu(k) \tag{4}$$

$$y(k) = cx(k) + du(k) \tag{5}$$

When the output y of controller is larger than the limit value y_{max}, y becomes y_{max}. Using difference between y and y_{max}, this paper prevents the windup phenomenon caused by the output saturation of PI controller. The proposed anti-windup algorithm for controller corrects state variable $x(k+1)$ as shown (6) and (7). And, the corrected $\tilde{y}(k)$ is shown in (8).

$$\tilde{u}(k) = u(k) - \frac{y(k) - y_{max}}{d} \tag{6}$$

$$\tilde{x}(k+1) = ax(k) + b\tilde{u}(k) \tag{7}$$

$$\tilde{y}(k) = cx(k) + d\tilde{u}(k). \tag{8}$$

At the current sampling period, this algorithm corrects state variable from $x(k+1)$ to $\tilde{x}(k+1)$. As the results, the controller has no windup phenomenon caused by its own

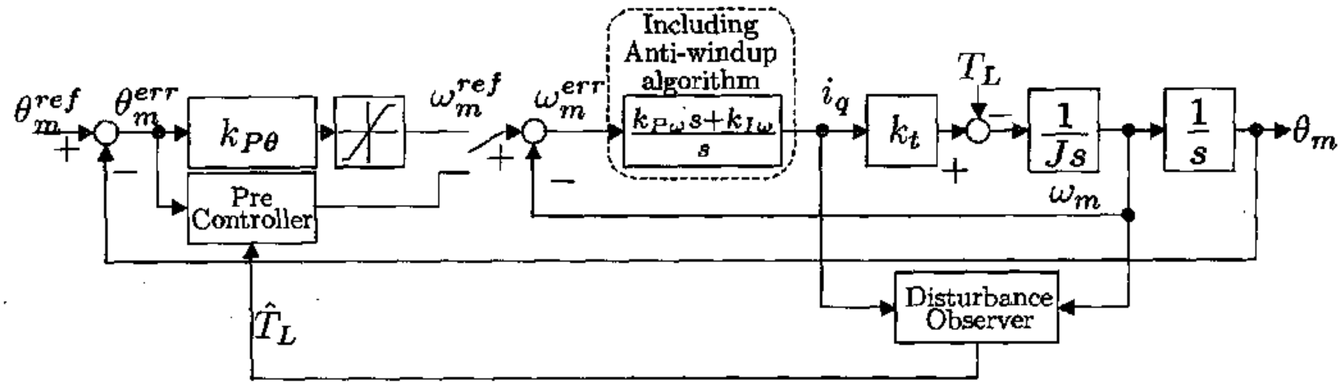

Fig. 8. Block diagram of proposed positioning system

output saturation. When y is smaller than y_{max}, this anti-windup algorithm is not executed.

Fig.9 shows the waveform of the ideal high speed positioning in the case of small position reference. In this case, the position error reaches $\Delta\theta_m^{err}$ before the motor speed reaches ω_{max}. Even in such case, the proposed algorithm is possible to finish the high speed positioning by using (3).

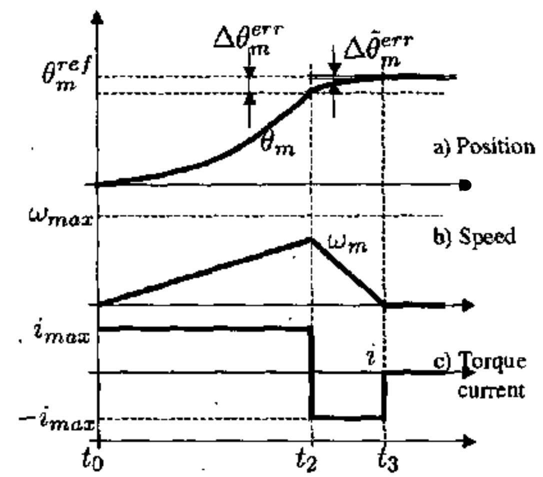

Fig. 9. Ideal waveform of high speed positioning system (short trip)

IV. Numerical Simulation Results

The numerical simulation is carried out in order to confirm the effectiveness of proposed high speed positioning algorithm. The conditions of numerical simulations are as follows:

1) without load torque, $\theta_m^{ref} = 6\pi$[rad]
2) with half load torque, $\theta_m^{ref} = 6\pi$[rad]
3) with half load torque, $\theta_m^{ref} = \pi$[rad]

The friction model of tested experimental system as shown in Fig.6 is shown in Fig.10 and Table III.

This paper designs the ordinary disturbance observer as shown in Fig.11. The disturbance observer which frequency band is 400[rad/s] and sampling time is 100[μsec]. In Fig.11, the gain g and T_s are defined as (9) and (10).

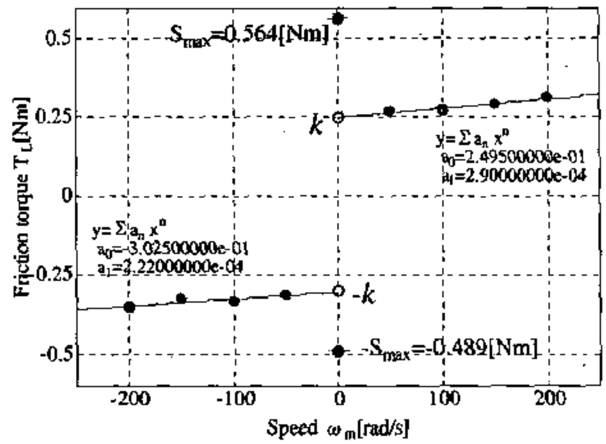

Fig. 10. Identification of friction model

TABLE III
FRICTION MODEL OF NUMERICAL SIMULATION

positive	maximum static		S_{max}[Nm]	0.564
	kinetic	viscous	D[Nm/rad/s]	2.9×10^{-4}
		coulomb	K[Nm]	2.495×10^{-1}
negative	maximum static		$-S_{max}$[Nm]	0.489
	kinetic	viscous	-D[Nm/rad/s]	2.22×10^{-4}
		coulomb	-K[Nm]	3.025×10^{-1}

$$g = 400 \tag{9}$$

$$T_s = 100 \times 10^{-6} \tag{10}$$

Each numerical simulation results are shown in Fig.12, Fig.13 and Fig.14. In Fig.12, the servo motor is accelerated by using the maximum torque current $+i_{max}$ without load torque, and the servo motor also is decelerated by using the maximum torque current $-i_{max}$. In Fig.13, it is confirmed that the servo motor similarly accelerates by using the maximum torque current $+i_{max}$ with half rated load torque. At last, the motor speed decelerates at the time t_2 based on the estimated coulomb friction torque $\hat{T}_L$, and the positioning control is finished. In Fig.14, the servo motor is accelerated by using the maximum current $+i_{max}$, and the deceleration mode

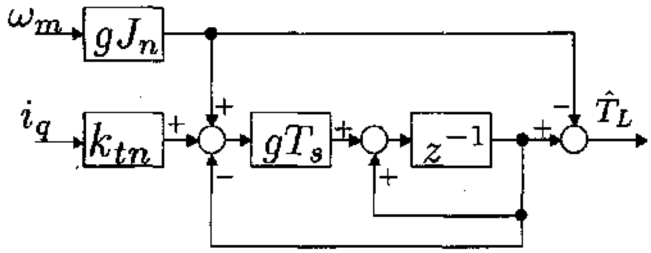

Fig. 11. Block diagram of disturbance observer

starts before the motor speed reaches ω_{max}. These numerical position responses are the desires responses, which are nearly equal to the ideal responses.

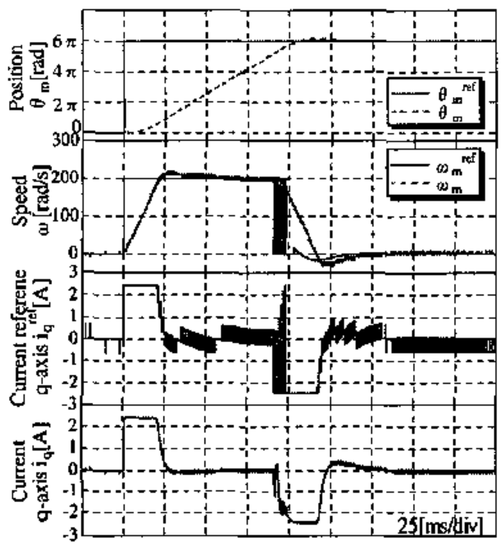

Fig. 12. Numerical simulation results (without load torque)

V. Experimental results

The experimental results without load torque are shown as in Fig.15, and Fig.16 is the experimental results with half load torque by Prony Brake System. Both experimental results are fine responses, since the acceleration mode and the deceleration mode are using the maximum torque current of servo motor on condition of any large torque. From the view point of Fig.4 and Fig.5, the proposed positioning system has more quick performance than the conventional positioning system. When the position reference is small as shown in Fig.17, the proposed positioning system also has high speed positioning performance. These experimental results are also the desired responses, which are also nearly equal to the ideal responses.

VI. Conclusion

This paper proposes a new high speed positioning system of AC servo motor considering unknown coulomb friction and windup phenomenon. The proposed always uses the maximum acceleration or deceleration torque and the maximum speed.

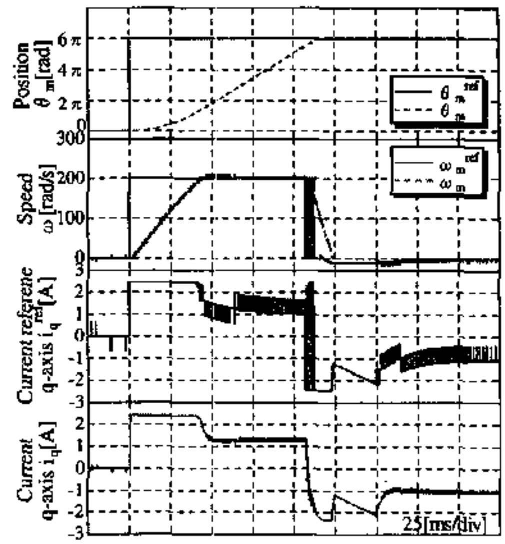

Fig. 13. Numerical simulation results (with half load torque)

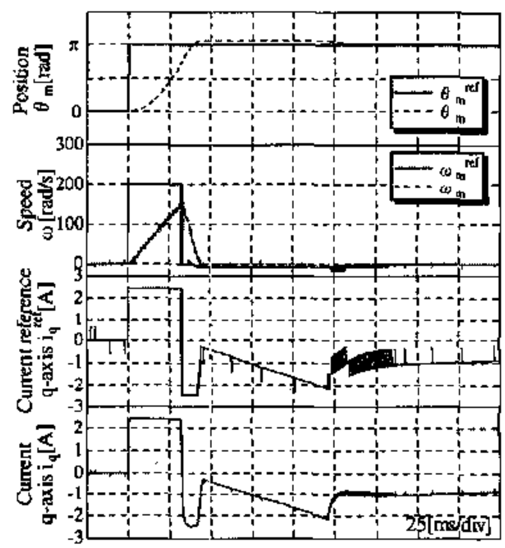

Fig. 14. Numerical simulation results (with half load torque, $\theta_m^{ref} = \pi$[rad])

The proposed algorithm uses the goal position and the coulomb friction load. In this paper, the coulomb friction load torque is estimated by disturbance observer.

In order to confirm the validity of proposed high speed positioning algorithm, this paper shows the numerical simulation results and the experimental results for position step response. The conditions of experiment and numerical simulation are as follows:

1) position reference $\theta_m^{ref} = 6\pi$[rad], without load torque
2) position reference $\theta_m^{ref} = 6\pi$[rad], with half load torque

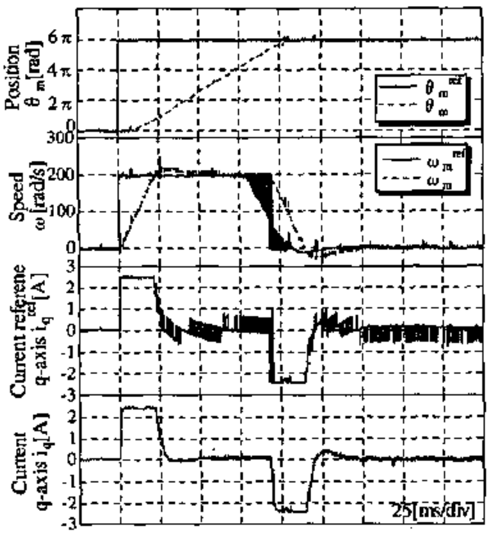

Fig. 15. Experimental results with proposed system (without load torque)

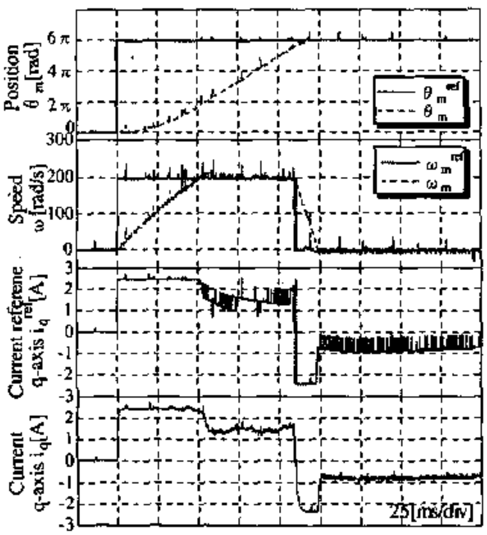

Fig. 16. Experimental results with proposed system (with half load torque)

3) position reference $\theta_m^{ref} = \pi$[rad], with half load torque

The experimental results and the numerical simulation results point out that the proposed high speed positioning system always has the desired position response, which is nearly equal to the ideal response.

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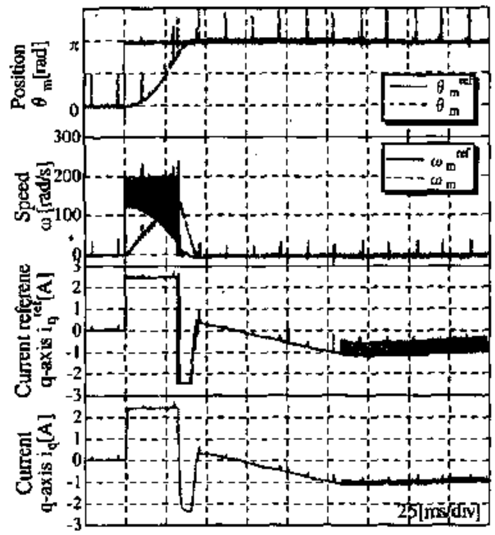

Fig. 17. Experimental results with proposed system ($\theta_m^{ref} = \pi$[rad])

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