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적응제어형 외란 관측기를 이용한 BLDC 전동기의 정밀위치제어에 대한 연구

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A Study on Adaptive Load Torque Observer for Robust Precision Position Control of BLDC Motor

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Abstract

A new control method for precision robust position control of a brushless DC (BLDC) motor using asymptotically stable adaptive load torque observer is presented in the paper. Precision position control is obtained for the BLDC motor system approximately linearized using the field-orientation method Recently, many of these drive systems use BLDC motors to avoid backlashes. However, the disadvantages of the motor are high cost and complex control because of nonlinear characteristics. Also, th load torque disturbance directly affects the motor shaft. The application of the load torque observer is published in [1] using fixed gain. However, the motor flux linkage is not exactly known for a load torque observer. There is the problem of uncertainty to obtain very high precision position control. Therefore a model reference adaptive observer is considered to overcome the problem of unknown parameter and torque disturbance in this paper. The system stability analysis is carried out using Lyapunov stability theorem. As a result, asymptotically stable observe gain can be obtained without affecting the overall system response. The load disturbance detected by the asymptotically stable adaptive observer is compensated by feedforwarding the equivalent current which gives fast response. The experimenta results are presented in the paper.

1. INTRODUCTION

Recently, DC motors have been gradually replaced by BLDC motors since the industry applications require more powerful actuators in small sizes. Th advantage of using a BLDC motor is that it can be controlled to have the speed-torque characteristics similar to that of a permanent magnet DC motor. In addition, the BLDC motor has low inertia, large power-to-volume ratio, and low noise as compared t permanent magnet DC servo motor having the same output rating [2]. However, the disadvantages are the high cost and more complex controller because o nonlinear characteristics [3]. The P-I (proportional-integral) controller is usually used in a BLDC moto control, which is simple in realization but difficult to obtain sufficiently high performance in the tracking application. It is, however, well-known that the tracking controller problem using state variable feedback can be simply solved by the augmentation of the state variables using the output error [4]. It is more efficient to obtain the control gain using optima control theory than the trial-and-error method for the P-I controller. For the unknown and inaccessible inputs, the observer technique was studied by [5]. Also, the application of the load torque observer with fixed gain was published [1]. However, the machine flux linkage is not exactly known for a load torque observer that gives the problem of uncertainty Therefore, a model reference adaptive observer was considered to overcome the problem of the unknown parameter in this paper [6]. But that is for the case of bounded input and bounded [BIBO] stable. So to reduce position error much more a new asymptotically stable load torque is needed. That problem is solved in this paper. The comparison between the two system which are fixed gain and adaptive gain system responses has been done in detail.

2. MODELING OF BLDC MOTOR

Generally, the behavior of a small horsepower BLDC motor used for position control is essentially th same as the permanent magnet synchronous machine. By means of field-oriented control, it is possible t make i_{ds} become zero[3]. Therefore, the system equations of a BLDC motor model can be described as

$$\dot{\omega}_r = \frac{3}{2}\frac{1}{J}\left(\frac{P}{2}\right)^2 \lambda_m i_{qs} - \frac{B}{J}\omega_r - \frac{P}{2J}T_L \quad (1)$$

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m i_{qs} \quad (2)$$

$$= k_t i_{qs} \quad (3)$$

$$\dot{y} = \omega_r \quad (4)$$

For implementation of field-orientation control, each of the three phase current control commands must be generated separately.

3. CONTROL ALGORITHM

The control reference in the drive is a step value as in a tracking servo problem. The dynamic equation of a given system can be expressed as follows:

$$\dot{x} = Ax(t) + bu(t) \quad (5)$$

$$\dot{y} = cx(t) \quad (6)$$

where the dimensions of the matrices A, b and c are $n\times n$, $n\times 1$ and $1\times n$, respectively. Usually, a linear quadratic controller is used to solve the regulato problem resulting in a state variable feedback. A new state is defined for the tracking controller as $\dot{z} = y - y_r$ where y_r is the rotor position reference [7]. The control input becomes $u = -kx - k_1 z$. From this equation, the state feedback controller gain can be obtained by the optimal control law minimizing the performance index with the weighting matrices Q and R. However, a large feedback gain is needed for fast reduction of error caused by the disturbance which results in a very large current command. If the load torque T_L is known, an equivalent current command i_{qc2} can be expressed as $T_L = k_t i_{qc2}$. Then, the load torque effect is compensated by feeding forward an equivalent q-axis current command to the output controller. But in the real system, there are many cases where some of the inputs are unknown or inaccessible. For simplicity, a 0-observer is selected. Thus, T_L can be considered as an unknown and assumed to be a constant. The system equation can be expressed as:

$$\begin{pmatrix} \dot{\hat{\omega}} \\ \dot{\hat{y}} \\ \dot{\hat{T}}_L \end{pmatrix} = \begin{pmatrix} -\frac{B}{J} & 0 & -\frac{P}{2}\frac{1}{J} \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{pmatrix} + \begin{pmatrix} k_t\frac{P}{2}\frac{1}{J} \\ 0 \\ 0 \end{pmatrix} i_{qs}$$

$$+L\left(y - (0\ 1\ 0)\begin{pmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{pmatrix}\right) \quad (7)$$

To guarantee the time required for calculating the load torque to be less than the overall system respons time and to compensate the load torque at transient state, a dead beat observer is desirable. It then follow from the Cayley-Hamilton theorem that $\Phi_c^n = 0$ where $\Phi_c = \hat{\Phi} - L\hat{c}$. The pole placement using Ackermann's formula can obtain the feedback gain L as follows: $L = P(\Phi) W_0^{-1}[0\ 0\ \ldots\ldots\ 1]$. Even though the observer feedback gain is obtained by using the nominal parameter value, there is a certain variation or uncertainty of the parameter, such as the machine flux linkage. To overcome this problem, an adaptive observer is considered [8]. In this system, the reference model is the real plant with the augmented state variable feedback controller. In a similar way the adaptive load torque observer is considered as an adjustable system. Eqn. (7) can be partitioned as follows:

$$\dot{x}_1 = Ax_1 + B_1 u - B_2\hat{T}_L \quad (8)$$

$$\dot{z} = c_1 x_1 - y_r \quad (9)$$

where $u = -K_1 x_1 - k_2 z + k_3\hat{T}_L$, K_1, k_2 and k_3 are $1\times n$ vector and two scalars, respectively. In the same way, the adaptive torque observer of (7) is described by

$$\dot{\hat{x}}_1 = A\hat{x}_1 + \hat{B}_1 u - B_2 T_L + L_1(c_1 x_1 - c_1\hat{x}_1) \quad (10)$$

$$\dot{\hat{T}}_L = l_3(c_1 x_1 - c_1\hat{x}_1) \quad (11)$$

where the ^ means estimated values. In order to derive the adaptive scheme, Lyapunov theorem is utilized.

From (8) - (10), the estimation errors of the rotor speed and rotor position are described by the following equation.

$$\dot{e}_1 = (A - L_1 c)e_1 + (B_1 - \widehat{B}_1)u - B_2(T_L - \widehat{T_L})$$
$$= Ge_1 + (B_1 - \widehat{B}_1)u - B_2(T_L - \widehat{T_L}) \quad (12)$$

where $e_1 = x_1 - \widehat{x}_1$ and $G = A - L_1 c$. Now, a new Lyapunov function candidate V is defined as follows:

$$V = e_1^T P e_1 + \frac{1}{\alpha}(B_1 - \widehat{B}_1)^T (B_1 - \widehat{B}_1)$$
$$+ \frac{1}{\beta}(T_L - \widehat{T_L})^2 \quad (13)$$

where P and α are a positive definite matrix and positive constant, respectively. The time derivative o V becomes

$$\dot{V} = e_1^T((A - L_1 c)^T P + P(A - L_1 c))e_1$$
$$+ 2\left(e_1^T u + \frac{1}{\alpha}\Delta\dot{\widehat{B}}_1^T\right)\Delta B_1 - 2\left(e_1^T B_2 + \frac{1}{\beta}\Delta\dot{\widehat{T_L}}\right)\Delta T_L \quad (14)$$

where $\Delta B_1 = B_1 - \widehat{B}_1$ and $\Delta T_L = T_L - \widehat{T_L}$. From (14), the adaptive mechanism can be obtained by equalizing the second term to zero as follows:

$$\dot{\widehat{B}}_1^T = -\alpha e_1^T u \quad (15)$$

The third term can be decreased to zero using the following equation:

$$\dot{\widehat{T_L}} = -\beta e_1^T B_2 = -\beta'(\omega_r - \widehat{\omega_r}) \quad (16)$$

where $\beta' = \frac{P}{2J}\beta > 0$. Therefore, the new adaptive torque observer can be obtained as

$$\dot{\widehat{T_L}} = l_3(c_1 x_1 - c_1\widehat{x}_1) - \beta'(\omega_r - \widehat{\omega_r}) \quad (17)$$

If we decide the observer gain matrix L_1 with optimal theory, the first term of (14) can be negative semi-definite. Assuming that there exists a positive definite matrix R such that

$$G^T P + PG = -R \quad (18)$$

the derivative of the Lyapunov function candidate can be written as

$$\dot{V} = -e_1^T(R)e_1 \leq 0. \quad (19)$$

Hence, e_1 is uniformly asymptotically stable. And the maximum error can be decreased by reducing the estimated load torque error and selecting the gain L_1 properly to make e_1 as zero. Discrete motor equation can be written as the following ARMA model:

$$y(k+1) = [\,y(k) \;\; y(k-1) \;\; y(k-2)\,][\,A_1 \;\; A_2 \;\; A_3\,]^T$$
$$+ [\,u(k) \;\; u(k-1)\,][\,B_1 \;\; B_2\,]^T. \quad (20)$$

where A_1, A_2, A_3, B_1 and B_2 are 1, $a_1 a_3/h$, $-a_1 a_3/h$, b_2 and $a_3 b_1$, respectively. In this case, B_1 and B_2 are not exact values. So, only these terms are expressed at the quasi term. Employing the definition of the new quasi-output can reduce the order of the estimated matrix. Then, quasi-output Y and model output Y_m can be obtained as the difference of real output and known values as follows:

$$Y(k+1) = (y(k+1) - \Phi_1\Theta_1) = \Phi_2\widehat{\Theta}_2 \quad (21)$$

$$Y_m(k+1) = b_2 i_{qc}(k) + a_3 b_1 i_{qc}(k-1). \quad (22)$$

Using, $E = Y(k+1) - Y_m(k+1)$ the gradient can be obtained as

$$\dot{\widehat{\Theta}}_2(k+1) = \widehat{\Theta}_2(k) - h\begin{pmatrix} a_1 i_{qc}(k) \\ a_2 a_3 i_{qc}(k-1) \end{pmatrix} E \quad (23)$$

where α_1 and α_2 are the elements of the vector α. The resultant block diagram of the model reference adaptive observer is shown in Fig. 1.

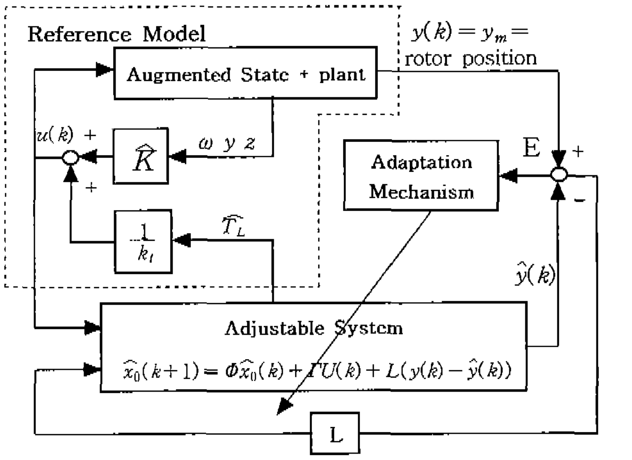


Fig.1. Configuration of the model reference adaptive torque observer

4. CONFIGURATION OF OVERALL SYSTEM

The block diagram of the proposed controller is shown in Fig. 2 where the controller is composed o two parts. The position controller is composed of th augmented state feedback. For the realization of the augmented state z(k+1), the discrete form of this state is approximately obtained by using a trapezoida rule. DSP TMS320C31 is used as a digital controller

An asymptotically stable load torque observer implements the other part. Estimated torque is used for compensation of position error. Motor system is driven by vector controller which make the system as linear system.

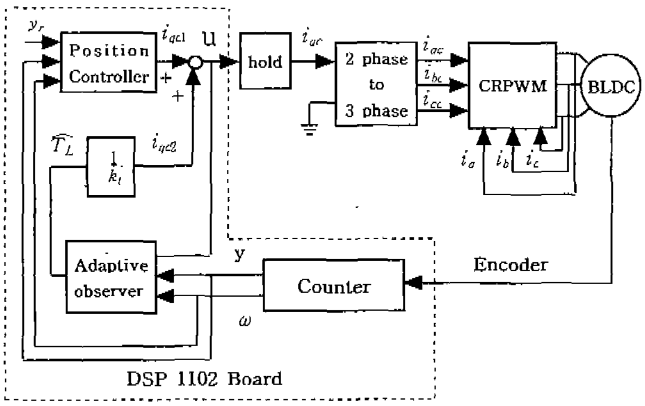


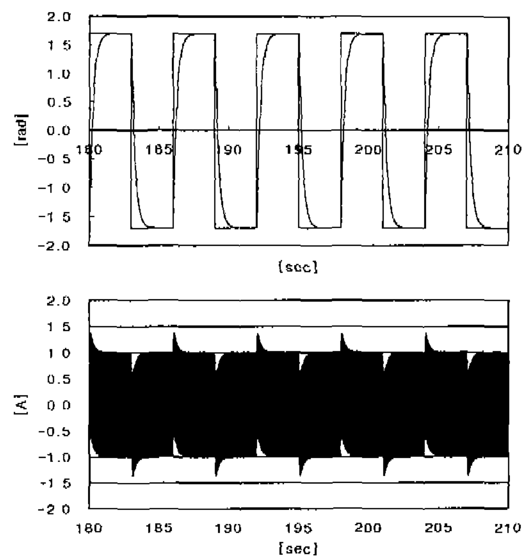
Fig. 2. Block diagram of the proposed precision position control system

5. SIMULATION AND EXPERIMENTAL RESULTS

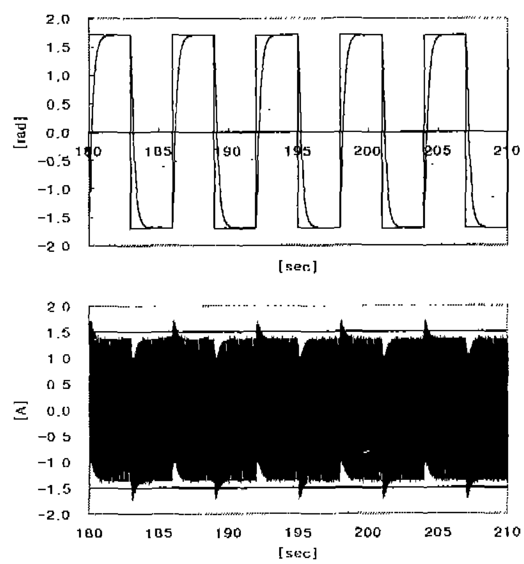
The parameters of a BLDC motor used in this experiment are given as follows:

Power	400 *watt*
Inertia	0.363×10^{-4} kgm^2
Rated torque	1.3 *Nm*
Rated current	2.7 *A*
Stator resistance	1.07 Ω/*phase*
Time constant	0.5 *ms*

The hysteresis-band gap is chosen as 0.05 A, and th sampling time Ts is determined as 0.1 *ms*. After some trial and error, the weighting matrix is selected as $Q = diag[\ 0.1\ \ 60\ \ 1000\ ]$, $R = 1$ and optimal gain matrix becomes $k = [\ 0.0598\ \ 2.0810\ \ 7.3540\ ]$. The nominal deadbeat observer gain becomes $L = [\ 21762\ \ 2.8187\ \ -1000.2\ ]$. In the adaptation mechanism, the adaptation rates α_1, α_2 and β' are obtained as 0.004, 0.002 and 0.025 by trial and error, respectively. The simulation results are in Fig. 3. Th deadbeat observe has a quite good result in point view of large scales as shown in Fig. 3(a). That current shows adaptive control action of reduction effort of algorithm is bigger than dead beat system.



(a) Dead beat control with load

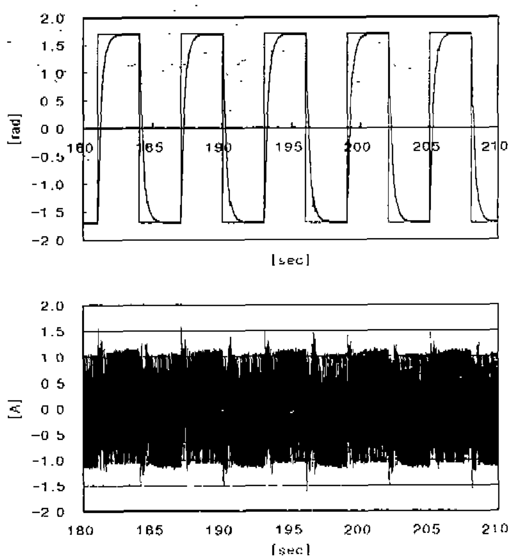


(b) Adaptive observer with load

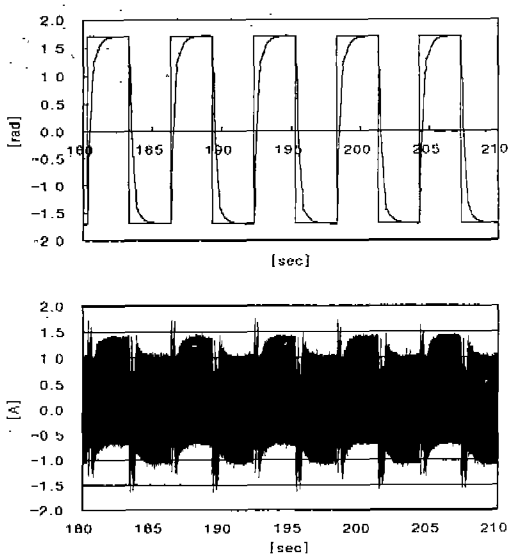
Fig 3. Simulation results of the rotor position and q phase current command

The experimental results are in Fig. 4, Fig. 5 and Fig. 6. The deadbeat observe has also a quite good result in point view of large scales as shown in Fig 4(a) as same as simulation. That current shows control action of reduction effort of algorithm. But there is a little chattering of position at bottom side

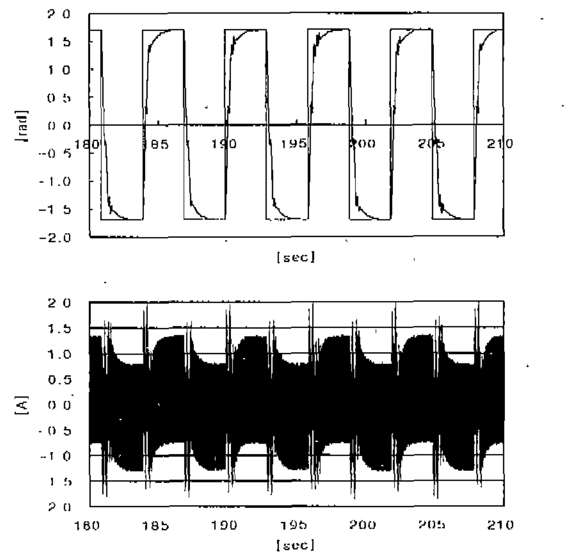
In Fig. 4(b) the different type control action is depicted. There is very small position error in not only upper side but also lower side. This indicate good adaptation to different condition. Current pattern is changed as a position response. And the difference can not detected in position result between unload case of Fig. 4(b) and loaded case of Fig. 4(c). As shown in Fig. 4(c), the magnitude of current in transient is increased up to 2[A] which has more control effect to reduce the effects of inertia load. Zoomed results are depicted in Fig. 5. In conventional case, error magnitude is not increase as increase load. But there is a little position chattering.



(a) Dead beat control with load



(b) Adaptive observer with no load



(c) Adaptive observer with load

Fig 4. Experimental results of the rotor position and q phase current command

This results came from parameter uncertainty about 20%. This small chattering decrease as shown in Fig 5(b). A processing of this algorithm is shown in Fig 6. It is started from Fig. 5(a) as a nominal gain. At beginning we can use this controller after about 3 minute which is a time for adapting. Next day, adapted data will be used for saving few minutes.

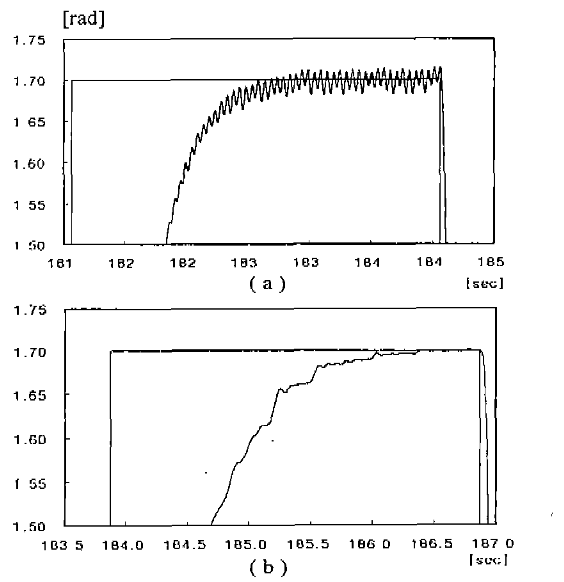


Fig 5. Performance comparison with dead beat and adaptive observers
(a) results of conventional dead beat observer
(b) results of proposed adaptive observer

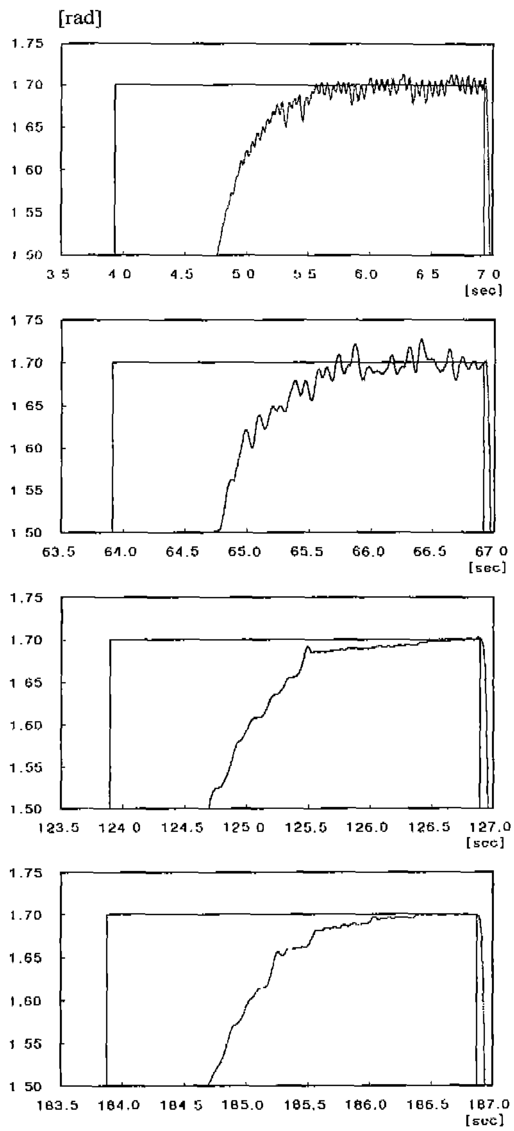


Fig 6. Process of successive adaptation with load

6. CONCLUSION

A load torque observer with the model reference adaptive system is used to obtain better performance from the BLDC motor in a precision position contro system. Also, the augmented state variable feedback is used in the digital experimental control system with an optimal gain. The system response comparison between the fixed dead beat gain observer and the adaptive observer has been done. The load torque compensator based on the adaptive observer and the feedforward injection can be used to cancel out the steady state and the transient position error due to the external disturbances, such as a various friction and load torque. The stability analysis is carried out usin Lyapunov stability theorem. Under this analysis, the new adaptive torque observer is proposed. In the proposed scheme, the rotor position error caused by non-exact parameter is decreased asymptotically. The total adaptive control system is realized by a digital controller DS1102(TMS320c31) with 0.1ms sampling time where the gain is obtained in z-domain using the optimal theory.

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