Asymptotically Stable Adaptive Load Torque Observer for Precision Position Control of BLDC Motor

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Abstract - A new control method for the robust position control of a brushless DC(BLDC) motor using the asymptotically stable adaptive load torque observer is presented. A precision position control is obtained for the BLDC motor system approximately linearized using the field-orientation method. And the application of the load torque observer is published in [1] using fixed gain. However, the flux linkage is not exactly known for a load torque observer. Therefore, a model reference adaptive observer is considered to overcome the problem of the unknown parameter in this paper. And stability analysis is carried out using Liapunov stability theorem. As a result, asymptotically stable observer 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 having the fast response.

I. INTRODUCTION

DC motors have been gradually replaced by the BLDC motor since the industry applications require more powerful actuators in small sizes. The 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 the low inertia, large power to volume ratio, and low noise as compared with the permanent magnet DC servo motor having the same output rating [2]. On the other hand, the disadvantages are the high cost and more complex controller caused by the nonlinear characteristics [3]. The PI controller is usually employed in a BLDC motor control, which is simple in realization but difficult to obtain the sufficiently high performance in the tracking application. It is, however, known that the tracking controller problem using a 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 the optimal control theory than the trial-and-error method for the PI controller. For the unknown and inaccessible inputs, the observer was studied by [5]. Also the application of the load torque observer is published using fixed gain[1]. However, the flux linkage is not exactly known for a load torque observer, there is a problem of uncertainty. Therefore, a model reference adaptive observer is considered to overcome the problem of the unknown parameter in this paper. The comparison between the two system responses has been done in detail.

II. MODELING OF BLDC MOTOR

Generally, a small horse power BLDC motor used for a position control is the same as a permanent magnet synchronous machine. The stator is constructed by three phase Y-connection without the neutral and the rotor is made by the permanent magnets. By means of a field-oriented control, it is possible to make i_{ds} become zero[3]. Therefore, the system equations of a BLDC motor model can be described as

$$\omega_r = \frac{3}{2}\frac{1}{J}\left(\frac{p}{2}\right)^2 \lambda_m i_{qs} - \frac{B}{J}\omega_r - \frac{p}{2J}T_l \quad (1)$$

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

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

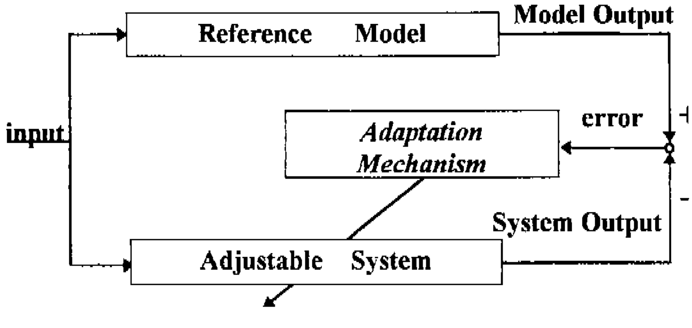

Fig. 1. Basic configuration of the MRAC

Since the current control is employed in a position control, the system model expressing the position dynamics becomes (1) and the rotor position dynamics becomes

$$y = \omega_r \tag{4}$$

For the implementation of the field-orientation, each three phase current control command must be generated separately. This command can be obtained by converting the controller current command based on the rotor reference frame to the stator reference frame.

III. CONTROL ALGORITHM

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

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

$$y = cx(t) \tag{6}$$

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 regulator problem resulting in a state variable feedback. A new state is defined for the tracking controller as $z = y - y_r$

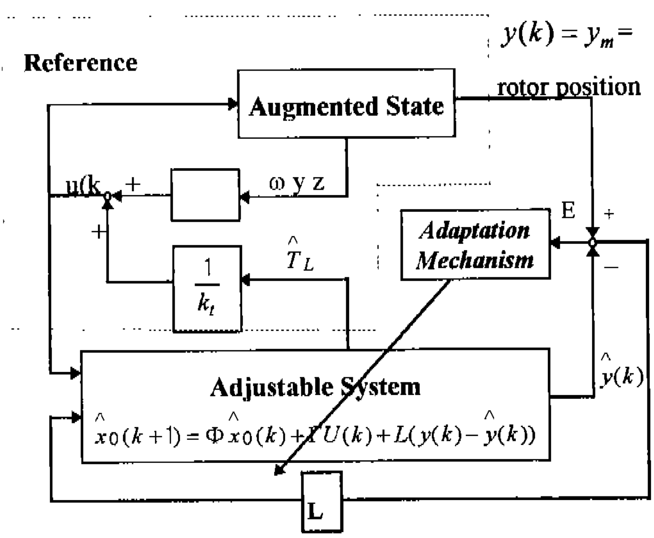

Fig. 2. Configuration of the proposed adaptive torque observer

where y_r is the rotor position reference [6]. 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 matrix Q and R. However, a large feedback gain is needed for the fast reduction of an error caused by the disturbance, which results in a very large current command. If the load torque T_L is known, a equivalent current command i_{qe2} can be expressed as $T_L = k_t i_{qe2}$. Then, the load torque effect is compensated by feeding forward an equivalent q axis current command to the output controller as shown in Fig. 2. Generally, to estimate a state, it is required to know all the inputs given to the system. 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

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

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

To guarantee the less time required calculating the load torque than the overall system response time and to compensate the load torque at transient state, a dead beat observer is desirable. It then follows from the Cayley-Hamilton theorem that the $\Phi_c^n = 0$ where $\Phi_c = \hat{\Phi} - L\hat{c}$. The feedback gain L can be obtained by the pole placement using Ackermann's formula as follows: $L = P(\Phi) W_o^{-1} [0 \ 0 \ \ldots \ 1]$. 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 flux linkage. To overcome this problem, an adaptive observer is considered. As shown in Fig. 1, the difference between the reference model and the adjustable system can be reduced by an adaptive mechanism [7]. 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. The (7) can be partitioned as follows:

$$x_1 = Ax_1 + B_1 u - B_2 \hat{T}_L \tag{8}$$

$$z = c_1 x_1 - y_r \tag{9}$$

where

$$u = -K_1 x_1 - k_2 z + k_3 \hat{T}_L$$

$$A = \begin{pmatrix} -\frac{B}{J} & 0 \\ 1 & 0 \end{pmatrix} \quad B_1 = \begin{pmatrix} k_t \frac{p}{2J} \\ 0 \end{pmatrix} \quad B_2 = \begin{pmatrix} \frac{p}{2J} \\ 0 \end{pmatrix} \quad c_1 = \begin{pmatrix} 0 & 1 \end{pmatrix}$$

K_1, k_2 and k_3 are $1 \times n$ vector and two scalars, respectively. As a same way, the adaptive torque observer of (7) is described by

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

$$\hat{T} = l_3\left(c_1 x_1 - c_1 \hat{x}_1\right) \tag{11}$$

where the ^ means a estimated values. In order to derive the adaptive scheme, Lyapunov theorem is utilized. From (8) through (10), the estimation error of the rotor speed rotor position is described by the following equation.

$$\begin{aligned} \dot{e}_1 &= (A - L_1 c)e_1 + \left(B_1 - \hat{B}_1\right)u - B_2\left(T_L - \hat{T}_L\right) \\ &= Ge_1 + \left(B_1 - \hat{B}_1\right)u - B_2\left(T_L - \hat{T}_L\right) \end{aligned} \tag{12}$$

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

$$V = e_1^T P e_1 + \frac{1}{\alpha}\left(B_1 - \hat{B}_1\right)^T\left(B_1 - \hat{B}_1\right) + \frac{1}{\beta}\left(T_L - \hat{T}_L\right)^2 \tag{13}$$

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

$$\begin{aligned} \dot{V} &= e_1^T\left((A - L_1 c)^T P + P(A - L_1 c)\right)e_1 + \\ & 2\left(e_1^T u + \frac{1}{\alpha}\Delta \dot{B}_1^T\right)\Delta B_1 - 2\left(e_1^T B_2 + \frac{1}{\beta}\dot{\hat{T}}_L\right)\Delta T_L \end{aligned} \tag{14}$$

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

$$\dot{\hat{B}}_1^T = \alpha e_1^T u \tag{15}$$

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

$$\dot{\hat{T}}_L = -\beta e_1^T B_2 = -\beta'\left(\omega_r - \hat{\omega}_r\right) \tag{16}$$

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

$$\hat{T} = l_3\left(c_1 x_1 - c_1 \hat{x}_1\right) - \beta'\left(\omega_r - \hat{\omega}_r\right). \tag{17}$$

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

$$G^T P + PG = -R \tag{18}$$

the derivative of the Lyapunov function candidate can be written as

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

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 following ARMA model:

$$y(k+1) = \left[y(k)\ \ y(k-1)\ \ y(k-2)\right]\left[A_1\ \ A_2\ \ A_3\right]^T + \left[u(k)\ \ u(k-1)\right]\left[B_1\ \ B_2\right]^T. \tag{20}$$

where A_1, A_2, A_3, B_1 and B_2 are 1, a_1a_3/h, $-a_1a_2/h$, b_2 and a_3b_1, respectively. In this case B_1 and B_2 are not exact values. So, only these terms are expressed at the quasi term. The order of the estimated matrix can be reduced by employing the definition of the new quasi output. Then,

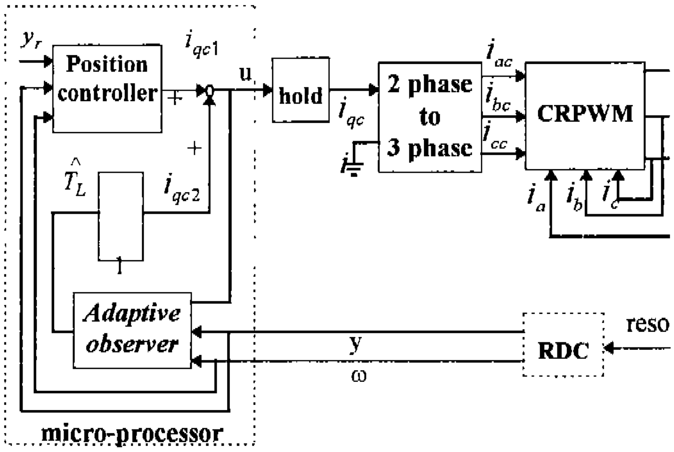

Fig. 3. Block diagram of the proposed digital position control system

quasi output and model output Y_m can be obtained as the difference of real output and known values as follows:

$$Y(k+1) = \left(y(k+1) - \Phi_1\Theta_1\right) = \Phi_2\hat{\Theta}_2 \tag{21}$$

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

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

$$\hat{\Theta}_2(k+1) = \hat{\Theta}_2(k) - h\begin{pmatrix}\alpha_1 i_{qc}(k) \\ \alpha_2 a_3 i_{qc}(k-1)\end{pmatrix}E \tag{23}$$

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. 2. During the operation, the quasi output Y from (20) is continuously compared to the model output Y_m. The obtained error E is used in an adaptive mechanism which adjusts the parameters in the primary controller in such a way that the process response becomes equal to that of the reference model. The block diagram of the proposed controller is shown in Fig. 3 where the controller is composed of two parts. The position controller is composed of the 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 trapezoidal rule. The power converter is controlled by the field orientation method, which is composed of a 2 phase to 3 phase converter and a CRPWM.

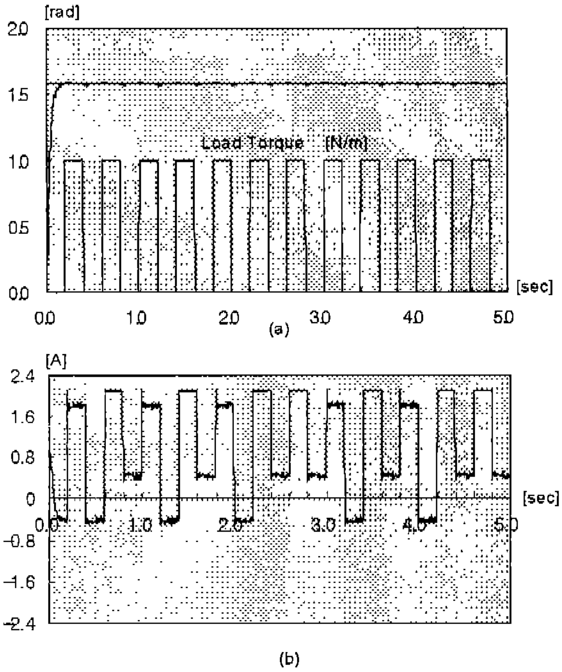

Fig. 4. Rotor position with load torque and q-phase current command of the fixed gain observer

IV. SIMULATION RESULTS

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

Power	120 $watt$	Rated current	2.1A
Inertia	1.3132×10^{-4} kgm^2	Stator resistance	6.2Ω
Rated torque	1.438Nm	Time constant	2.89ms

The hysteresis band gap   is chosen as 0.05 [A] and the sampling time h is determined as 0.1 [ms]. After some trial and error, the weighting matrix is selected as $Q = diag\left[10^{-1}\ \ 10^{3}\ \ 10^{6}\right]$, R = 1 and optimal gain matrix becomes $K = \left[0.2501\ \ 34.82\ \ 857.1\right]$. The nominal dead beat observer gain becomes $L = \left[22468\ \ 3\ \ -6254\right]$. In the adaptation mechanism, the adaptation rates α_1, α_2 and β' are obtained as 0.4, 0.2 and 0.1 by trial and error, respectively. The simulation results of the conventional and proposed algorithms are depicted in Figs. 4 through 6. The parameter variation is also considered about 25 percent. As shown in Fig. 4, the step response of the rotor position is sensitive to the change of the load torque T_L .

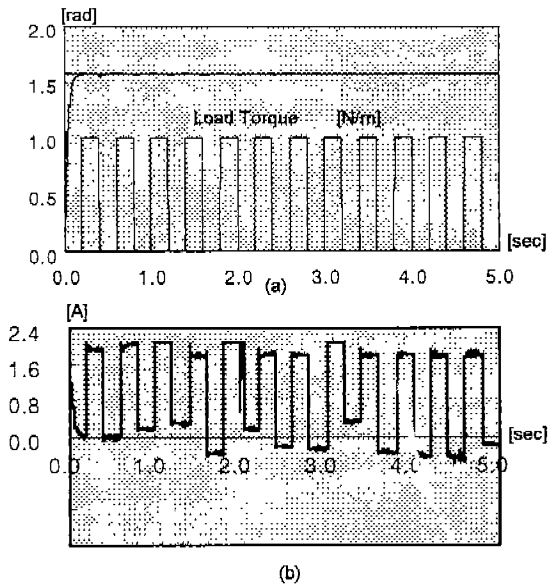

Fig. 5. Rotor position with load torque and q-phase current command of the proposed adaptive observer

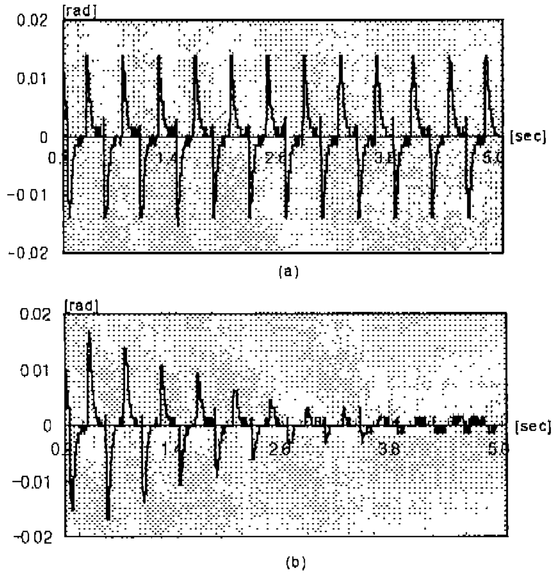

Fig. 6. Rotor position errors of the fixed gain obsever and proposed adaptive observer

This change of the load torque creates the position error about 0.018 [rad] as illustrated in Fig. 4(a). This unwanted error is caused by a non-exact parameter value. However, in the proposed scheme shown in Fig. 5(b), the position error is reduced gradually to 0.002 [rad] under the all operating conditions. This result is come from the adaptive load torque observer with the adaptive mechanism given by (23) and the feedforward compensation.

V. CONCLUSIONS

A load torque observer using the model reference adaptive system is employed to obtain the better performance from the BLDC motor in a position control. Also the augmented state variable feedback is employed in the digital control system with an optimal gain. The system response comparison between the fixed gain observer and the adaptive observer has been done. The load torque compensator based on the adaptive observer and the feedforward 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 a load torque. And stability analysis is carried out using Liapunov stability theorem. Under this analysis, the new adaptive torque observer is proposed. In this proposed scheme, the rotor position error caused by the non-exact parameter is decreased gradually. And the total control system can be realized by a digital controller where the gain is obtained in z-domain using the optimal theory.

VI. REFERENCES

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