Self-tuning Controller for Servo Motor with an Adaptive Disturbance Observer

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***Abstract*—In this paper, the state-space disturbance observer was successfully applied to servo motors to estimate and compensate for load variation. Furthermore, an auto-tuning procedure was developed accordingly to identify the varied parameters for state-space disturbance observer of the motor. Then, a real-time IP position controller based on identified parameters is designed by neural network for permanent magnet synchronous motor (PMSM) servo system. The neural networks configuration is simple and reasonable, and the weight has definitely physical meaning. It has rapidly adjusting character to realize the real-time control. The simulation results show that the proposed control scheme not only enhances the fast tracking performance, but also increases the robustness of the servo system.**

Keywords- disturbance observer; identification; servo system ;self-tuning; neural network

I. INTRODUCTION

Servo motors implemented in computerized numerical control (CNC) machine tools are widely applied to modern manufacturing processes to ensure precision of machining products[1]. Unavoidably, uncertainties may seriously degrade motion precision occurring in the current loop, the velocity loop, and the position loop. Moreover, the load and external cutting force are varied in practice. All those uncertainties are mutually coupled in different loops and lead to the degradation of motion accuracy in real applications using precise model design.

In the past decade, many modern control theories, such as nonlinear control [2], optimal control [3], variable structure system control [4], adaptive control [5], [6], and robust control [7] have been developed for the PM synchronous motor drive to deal with these uncertainties.

In real applications, if sources of disturbance and uncertainties can be properly identified, appropriate actions can be taken accordingly with further compensation. The digital disturbance observer (DOB) is efficient for disturbance estimation and rejection [8],[9].

Katsura et al. [10] adopted the accelerometer to achieve a torque observer with a wide bandwidth, while Lee and Blaabjerg [11] applied the inertia observer to estimate the inertia at low-speed performance. She et al. [12] proposed the estimation of an equivalent input disturbance to improve disturbance rejection for servo motor control systems.

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In this paper, a state-space DOB is designed to suppress load disturbance. Then, the system's model is greatly simplified when the disturbance observer is combined with the motor. Relying on the simplified model, a natural adaptive observer is used to estimate the motor parameters by minimizing the state estimation error using an iterative gradient algorithm offered by the affine projection arithmetic (APA). The estimated parameters are used to update the parameters of disturbance observer. Furthermore, an IP speed controller is introduced and online implemented based on neural network.

II. ADAPTIVE DOB

A. DOB modeling for servo motors

In PMSM, excitation flux is set-up by magnets; subsequently no magnetizing current is needed from the supply. This easily enables the application of the flux orientation mechanism by forcing the d axis component of the stator current vector to be zero. As a result, the electromagnetic torque will be directly proportional to the q axis component of the stator current vector; hence better dynamic performance is obtained by controlling the electromagnetic torque separately. A system configuration of a vector-controlled PMSM servo motor is shown in figure 1. In the vector control scheme, torque control can be carried out by suitable regulation of the stator current vector; this implies that accurate speed control depends on how well the current vector is regulated. In high-performance vector drives, a current control loop, with a considerably high bandwidth, is necessary to ensure accurate current tracking, to shorten the transient period as much as possible.

Assuming perfect current tracking, the actual torque producing current component can be replaced with the reference one. Accordingly, the electromechanical dynamics can be reasonably given in differential equation as

$$T_e = p_{\mathrm{n}}\psi_{\mathrm{f}} i_{\mathrm{q}}^* = K_t i_{\mathrm{q}}^* \tag{1}$$

$$T_{\mathrm{e}} = T_{\mathrm{L}} + B\omega + J\frac{\mathrm{d}\omega}{\mathrm{d}t} \tag{2}$$

where

ω the machine angle velocity of rotor, [Rad/s];
p_{n} number of magnetic poles;
T_{e} electromagnetic torque, [Nm];
T_{L} load torque, [Nm];
B viscous damping coefficient, [Nm.s];
J moment of inertia of the motor,[kg/m^2];

i_q^* q-axis command current component, [A];

ψ_f PM flux linkage in synchronous frame, [Wb].

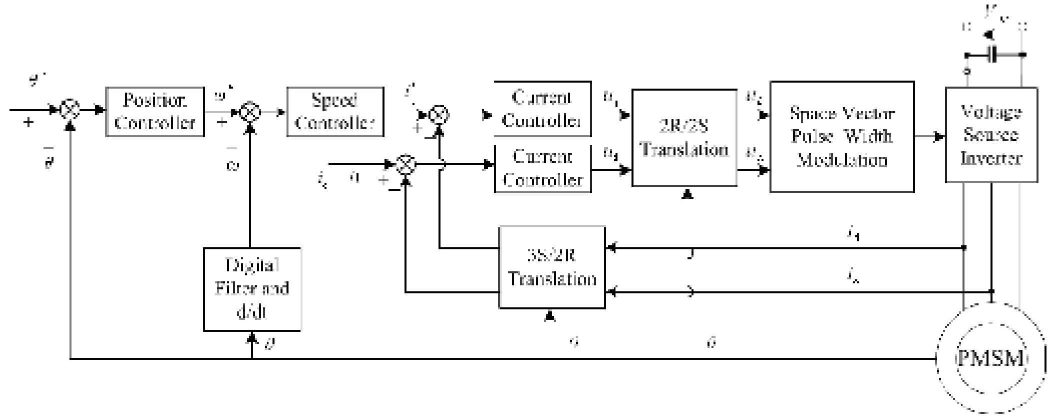

Figure 1. System configuration of vector-controlled servo motor

Based on (1) and (2), the plant dynamics in z-domain, with the zero order-hold (ZOH) conversion, can be given by

$$\omega(z) = \frac{b\left[i_q^*(z) - i_L(z)\right]}{z - a} \tag{3}$$

Where, $a = \exp(-TB/J)$, $b = K_t(1-a)/B$, T is the sampling period.

The time-sequence form of (3) is given by

$$\omega(k+1) - a\omega(k) = b\left[i_q^*(k) - i_L(k)\right] \tag{4}$$

It is assumed that the time constant of the disturbance load torque variation is much larger than that of a servo controller. Thus the variation of the disturbance load torque can be considered as zero. Therefore, by defining the system states of the DOB as the rotation velocity $\omega(k)$ and the external loading disturbance $i_L(k)$ as

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{\Phi}\boldsymbol{x}(k) + \boldsymbol{\Gamma}\boldsymbol{u}(k) \\ y(k) &= \boldsymbol{H}\boldsymbol{x}(k) \end{aligned} \tag{5}$$

Where, $\boldsymbol{\Phi} = \begin{bmatrix} \hat{a} & -\hat{b} \\ 0 & 1 \end{bmatrix}$, $\boldsymbol{\Gamma} = \begin{bmatrix} \hat{b} \\ 0 \end{bmatrix}$ $\boldsymbol{H} = \begin{bmatrix} 1 & 0 \end{bmatrix}$, $\boldsymbol{x}(k) = \begin{bmatrix} \omega(k) \\ i_L(k) \end{bmatrix}$

$y(k) = \omega(k)$, $\boldsymbol{u}(k) = i_q^*(k)$

Considering (5), the full order state estimator for this system can be arranged as:

$$\begin{bmatrix} \hat{\omega}(k+1) \\ \hat{i}_L(k+1) \end{bmatrix} = \boldsymbol{\Phi}\begin{bmatrix} \hat{\omega}(k) \\ \hat{i}_L(k) \end{bmatrix} + \boldsymbol{\Gamma} i_q^*(k) + \boldsymbol{L}\left(\omega(k) - \boldsymbol{H}\begin{bmatrix} \hat{\omega}(k) \\ \hat{i}_L(k) \end{bmatrix}\right) \tag{6}$$

where $\boldsymbol{L}=[l_1, l_2]^T$ is the gain matrix.

The parameters $\hat{a}$ and $\hat{b}$ of the DOB can self-tuning based on parameter estimation in next section.

B. Parameters Estimation Using an Adaptive Observer

Considering the motor and the disturbance observer as a one system, the system's model is greatly simplified. Under perfect disturbance compensation, the drive model can be written as

$$\omega(z) = \frac{bz^{-1}}{1 - az^{-1}} i_q^*(z) \tag{7}$$

The time-sequence form of (7) is given by

$$\omega(k) = a\omega(k-1) + bi_q^*(k-1) \tag{8}$$

Relying on the simplified model in (8), a simple natural state observer can be constructed to estimate the motor speed as follows:

$$\hat{\omega}(k) = \hat{a}\hat{\omega}(k-1) + \hat{b}i_q^*(k-1) \tag{9}$$

where $\hat{\omega}_{ob}$ is the observer output and $\hat{a}$, $\hat{b}$ are the observer parameters. The state estimation error can be defined as

$$e(k) = \omega(k) - \hat{\omega}(k) \tag{10}$$

The state estimation error will be produced due to any mismatch between the estimated speed and the predicted one. This error is produced mainly by parameters variation. Accordingly, the state estimation error can be used to adaptively adjust the observer parameters in a manner that minimizes the error. At this condition, the estimated parameters will converge to their real (actual) values.

To minimize the state estimation error, an iterative gradient algorithm, based on the APA is used. The height space of the APA is the state estimation error. The vector representation of (8) is given by

$$\omega(k) = \boldsymbol{R}^T(k-1)\boldsymbol{\theta}(k-1) \tag{11}$$

Where,

$\boldsymbol{R}(k-1) = [\omega(k-1), i_{q1}(k-1)]^T$, $\boldsymbol{\theta}(k-1) = [a(k-1), b(k-1)]^T$,

In (11), the vectors $\boldsymbol{R}$ $(k-1)$ and $\boldsymbol{\theta}(k-1)$ are, respectively, the measurement input/output vector and the parameters vector.

The estimate vector,

$$\hat{\boldsymbol{\theta}}(k-1) = [\hat{a}(k-1), \hat{b}(k-1)]^T \tag{12}$$

is recursively updated using the APA as follows:

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \frac{r\boldsymbol{R}(k-1)e(k)}{\varepsilon + \boldsymbol{R}^T(k-1)\boldsymbol{R}(k-1)} \tag{13}$$

where $r \in (0,2)$ is the reduction factor and ε is a small value to avoid division by zero if $\boldsymbol{R}^{\mathrm{T}}(k-1)\boldsymbol{R}(k-1)=0$

It should be noted that the proposed adaptive observer, described by (11)–(13), satisfies the convergence criterion as

$$\lim_{k\to\infty}\frac{e(k)}{\sqrt{\varepsilon+\boldsymbol{R}^{\mathrm{T}}(k-1)\boldsymbol{R}(k-1)}}=0 \tag{14}$$

III. Real-time IP Control Based on Neural Network

A. IP Speed Controller for Servo System

To match the requirements of high-performance applications, the desired specifications of position step command tracking usually are: 1) no overshoot; 2) no steady state error; and 3) preset of rise time. An IP controller capable of satisfying the above specifications is adopted in this system as shown in figure 2. The systematic design procedure of the IP position controller is discussed in [19].

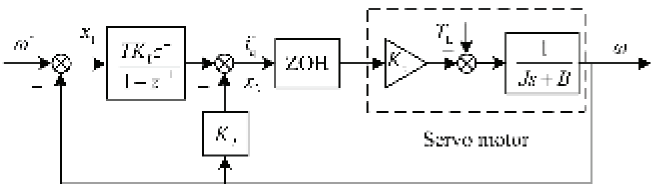

Figure 2. Simplified control system block diagram

The z-domain transfer function between the predicted speed and the reference one is given by

$$\frac{\omega(z)}{\omega^{*}(z)}=\frac{bK_{\mathrm{I}}T}{z^{2}-(1+a-bK_{\mathrm{P}})z+\left[a+b(K_{\mathrm{I}}T-K_{\mathrm{P}})\right]} \tag{15}$$

where K_{I} and K_{P} are the integral and proportional gains of the IP controller respectively. Using the bandwidth method, the controller gains can be derived to achieve the time domain tracking specifications. The self-tuning controller gains can be calculated as

$$\begin{aligned}K_{\mathrm{I}}&=\frac{1}{bT}\left[\exp(-2\zeta\omega_{n}T)+bK_{\mathrm{P}}-a\right]\\K_{\mathrm{P}}&=\frac{1}{b}\left[1+a-2\exp(-2\zeta\omega_{n}T)\cdot\cos\left(\omega_{n}T\sqrt{1-\zeta^{2}}\right)\right]\end{aligned} \tag{16}$$

where ζ is the damping ratio and ω_n is the natural frequency of the characteristic equation of (16).

B. Real-time IP Controller Based on Neural Network

In order to increase the robustness of the system, the IP controller is online implemented based on neural network. Equation (17) and (18) can be obtained from the IP controller in figure 2.

$$x_{1}(k)=\omega^{*}(k)-\omega(k) \tag{17}$$

$$x_{2}(k)=x_{2}(k-1)+TK_{\mathrm{I}}x_{1}(k-1)-K_{\mathrm{P}}\left(\omega(k)-\omega(k-1)\right) \tag{18}$$

So, the designed neural network framework is as shown in figure 3.

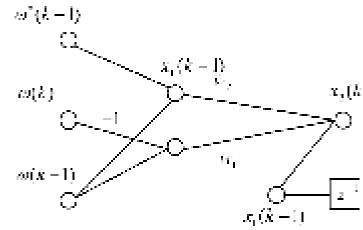
Figure 3. IP position controller realized by neural network

In order to improve response speed of the system, the initial weight value of the position controller is not a small random number, but rather makes $w_1(0)=K_{\mathrm{P}}$ and $w_2=TK_{\mathrm{I}}$. It shows the weight has its own clear physical meaning, and there is corresponding relation between the weight and the IP controller parameters. Neural network has the weight which can adjust itself on-line. It also realizes the real-time control, has good robustness.

The adjustment is realized mainly by the speed closed loop when parameters changes. When the neural network regulation is used in IP controller, learning rule of the weight is as follows:

$$w_{1}(k+1)=w_{1}(k)+d_{1}\Delta a+d_{2}\Delta b \tag{19}$$

$$w_{2}(k+1)=w_{2}(k)+d_{3}\Delta a+d_{4}\Delta b \tag{20}$$

Where, Δa and Δb are the estimated incremental value of a and b, namely, $\Delta a=\hat{a}-a$, $\Delta b=\hat{b}-b$; d_1, d_2, d_3 and d_4 are the coefficient under the different requirements of performance.

IV. Simulations and Discussions

To evaluate the proposed control scheme, various digital simulations were undertaken. Some simulation results are presented here. The parameters of the PMSM used in simulation research are as follows:

TABLE I. PARAMETERS OF PMSM

Rated power P_{N}(kW)	1
Rated voltage U_{N}(V)	150
magnetic pole pairs p	4
Rated speed(r/min)	2000
Inertia J(kg/m^2)	0.0087
Viscous coefficient B(Nm.s)	0.0005
Stator resistance R_{s} (Ω)	0.53
d-axis stator inductance L_{d} (mH)	2.25
q-axis stator inductance L_{q} (mH)	2.25
Rotor flux linkage Ψ_{f}(Wb)	0.175

The sampling interval of the control processing in simulations is set at 0.002s. For investigating the effectiveness of the proposed controllers, two kinds of uncertainties, parameter variations of the shaft and load torque disturbance, are considered here. Two cases for plant transfer function are considered as follows:

Case#1: Nominal parameters.

(J_1=J=0.0087, B_1=B=0.0005)

Case#2: Non-nominal parameters.

(J_2=2J=0.0174, B_1=2B=0.001)

According to the above case, two simulation results are given here. In the first simulation, the servo system is in case#1. The step rotor speed commands (step command 100rad/s) are given. The load torque with 2 Nm is given at the beginning of the simulation and becomes 5Nm at 0.8s. The simulation results with the proposed control scheme are shown in figure 4 and figure 5. Figure 4 shows the load torque observe curve, figure 5 shows the speed step response curve of the speed control system. Figure 4 and figure 5 show that the state-space DOB can observe the load torque truly and the servo system has good static and dynamic performance.

In the second simulation, the servo system is in case#2. The simulation results without and with the proposed control scheme are shown in figure 6. The green curve represents the simulation results of the servo system with the proposed control scheme. The blue curve represents the simulation results of the servo system with conventional DOB and fix gain IP controller.

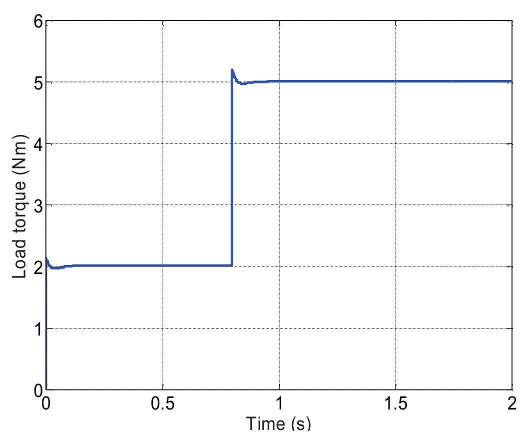

Figure 4. Load torque observe curve of the servo system

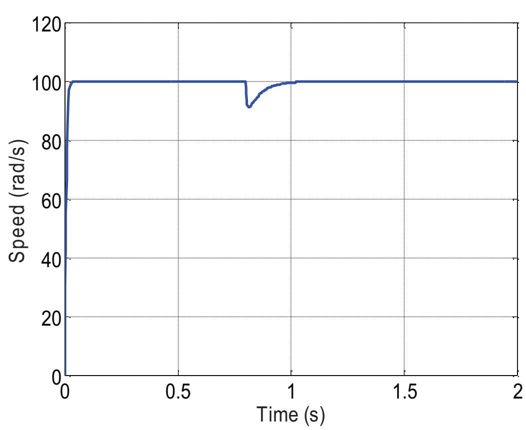

Figure 5. Speed step response plot of the servo system

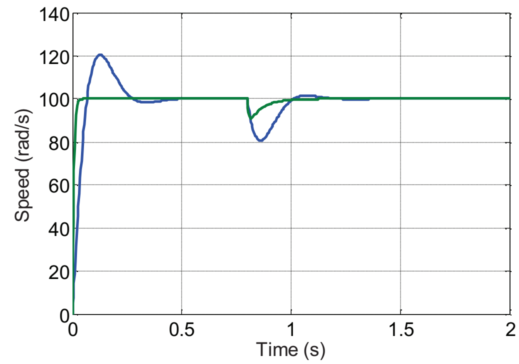

Figure 6. Speed step response curve of the servo system

Obviously, the servo system based on proposed control scheme has much better dynamic response in both tracking and regulation responses than that based on traditional fixed gain IP control scheme when motor parameter variation.

V. Conclusion

A robust servo system has been presented in this paper. A state-space DOB is designed to suppress load disturbance first. Then, the system's model is greatly simplified when the disturbance observer is combined with the motor. Relying on the simplified model, a natural adaptive observer was used to estimate the motor parameters by minimizing the state estimation error using an iterative gradient algorithm offered by the affine projection. The estimated parameters were used to update the parameters of disturbance observer synchronously. Furthermore, an IP speed controller was introduced and was online implemented based on neural network. The theoretical basis of the proposed real-time controller and observer were derived, and the effectiveness of the proposed controller was confirmed by the simulation results.

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