Robustness improvement of DC motor speed control using communication disturbance observer under uncertain time delay

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The speed control problem of a time-delay DC motor system is proposed because the control performance can severely deteriorate under uncertain delay time information. Since most of existing delay compensators require exact system parameters and delay time information, the performance improvement has been limited under delay time uncertainty. The proposed method incorporates a disturbance observer on the slave side of the system with a communication disturbance observer that does not require the delay time information for generating a predicted output signal. The effectiveness of the proposed algorithm is tested through comparative simulations and experiments using a testbed system under large delay time uncertainty.

Introduction: This Letter considers a DC motor speed control problem under time delay as shown in Fig. 1. If the armature inductance is sufficiently small, the DC motor model can be represented by

$$\dot{\omega}_s(t) = -\frac{1}{\tau}\omega_s(t) + \frac{k}{\tau}\left\{v_s(t) - \alpha T_L(t)\right\} \tag{1}$$

where ω_s, v_s, and T_L represent the rotor speed, the input voltage, and the load torque disturbance, respectively. The parameters $\alpha = R_a/K_t$, $\tau = K_t/(BR_a + K_t K_b)$, and $k = JR_a/(BR_a + K_t K_b)$ where R_a is the armature resistance; K_t and K_b are the torque and the back electromotive force constants; and J and B represent the rotor inertia and the friction coefficient, respectively. The transfer function $G(s)$ and its nominal one $G_n(s)$ are given by

$$G(s) = \frac{k}{\tau s + 1}, \quad G_n(s) = \frac{k_n}{\tau_n s + 1} \tag{2}$$

where k_n and τ_n denote the nominal values of k and τ, respectively.

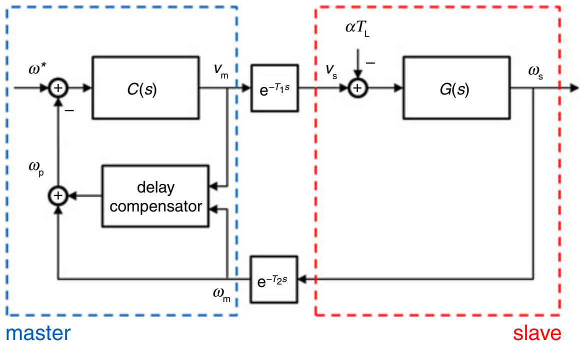

Fig. 1 *Control system with delay compensator*

Let ω_m and v_m be the velocity and the input voltage on the master side shown in Fig. 1. Considering the time delays (T_1, T_2) and parametric uncertainties, (1) can be rewritten as

$$\dot{\omega}_s(t) = -\frac{1}{\tau_n}\omega_s(t) + \frac{k_n}{\tau_n}\left\{v_m(t - T_1) - d(t)\right\} \tag{3a}$$

$$\omega_m(t) = \omega_s(t - T_2) \tag{3b}$$

where d is an equivalent disturbance input that includes T_L and parameter uncertainties as well.

To deal with the performance degradation owing to the time delays, various schemes using delay compensators have been incorporated with the main controller $C(s)$ as shown in Fig. 1. Among the delay compensators, this Letter first investigates the well-known Smith predictor [1] and communication disturbance observer (CDOB) [2]. Since those methods show limited performances under uncertain delay time information and/or external disturbances, a novel control structure is presented by combining a disturbance observer [3, 4] on the slave side as shown in Fig. 2. Comparative simulations and experimental results prove the effectiveness of the proposed method.

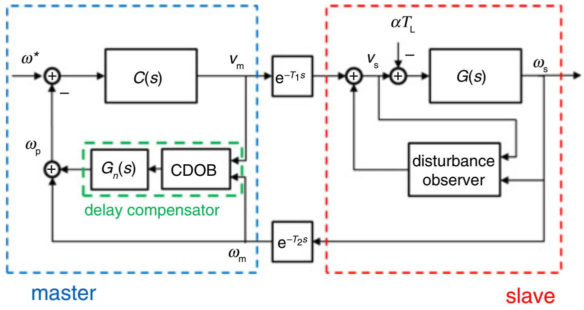

Fig. 2 *Structure of the proposed control method*

Smith predictor and CDOB methods: This section briefly reviews two existing methods for time delay compensation under ideal conditions with no uncertainty. When $d = 0$, Laplace transform of (3) is given by

$$\Omega_m(s) = G_n(s)e^{-Ts}V_m(s), \quad T = T_1 + T_2 \tag{4}$$

Smith predictor adds a predicted correction term Ω_{smith} to the delayed measurement $\Omega_m(s)$ as follows:

$$\Omega_{smith}(s) = G_n(s)(1 - e^{-Ts})V_m(s) \tag{5}$$

$$\Omega_p(s) = \Omega_m(s) + \Omega_{smith}(s) = G_n(s)V_m(s) \tag{6}$$

By using (6), the closed-loop transfer function $G_{cl}(s)$ is given by

$$G_{cl}(s) = \frac{C(s)G_n(s)}{1 + C(s)G_n(s)}e^{-Ts} \tag{7}$$

If there is no uncertainty, time delays do not influence on the stability of the closed-loop system (7). However, Smith predictor requires the exact delay time and system information to ensure a desired performance that can be hardly achieved without an additional algorithm under various uncertainties.

The CDOB approach estimates a network disturbance for composing the predicted output $\omega_p(t)$ in Fig. 1 [2]. When $d = 0$ in (3), the equation can be rewritten as

$$\dot{\omega}_s(t) = -\frac{1}{\tau_n}\omega_s(t) + \frac{k_n}{\tau_n}\left\{v_m(t) - d_1(t)\right\} \tag{8a}$$

$$\omega_m(t) = \omega_s(t) - d_2(t) \tag{8b}$$

where $d_1(t) = v_m(t) - v_m(t - T_1)$ and $d_2(t) = \omega_s(t) - \omega_s(t - T_2)$. Laplace transform and some calculations yield

$$\Omega_m(s) = G_n(s)\left\{V_m(s) - D_{net}(s)\right\} \tag{9}$$

where $D_{net}(s) = D_1(s) + G_n^{-1}(s)D_2(s)$ is the network disturbance. Assuming $\dot{d}_{net} = 0$, (9) can be realised as

$$\dot{z}_m(t) = Az_m(t) + Bv_m(t), \quad \omega_m(t) = Cz_m(t) \tag{10}$$

where

$$z_m = \begin{bmatrix} \omega_m \\ d_{net} \end{bmatrix}, \quad A = \begin{bmatrix} -\frac{1}{\tau_n} & -\frac{k_n}{\tau_n} \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \frac{k_n}{\tau_n} \\ 0 \end{bmatrix}, \quad \text{and} \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

Based on (10), the CDOB is constructed to estimate the network disturbance d_{net} as follows:

$$\dot{\hat{z}}_m(t) = A\hat{z}_m(t) + Bv_m(t) + L_m\left\{\omega_m(t) - \hat{\omega}_m(t)\right\} \tag{11}$$

where $\hat{z}_m = \begin{bmatrix} \hat{\omega}_s & \hat{d}_{net} \end{bmatrix}^T$. The observer gain L_m is designed such that $(A - L_m C)$ is stable. The estimate $\hat{d}_{net}(t)$ is used to make the correction term $\Omega_{cdob}(s) := G_n(s)\hat{D}_{net}(s)$ and the predicted output $\omega_p(t)$ is obtained by

$$\Omega_p(s) = \Omega_m(s) + \Omega_{cdob}(s) \approx G_n(s)V_m(s) \tag{12}$$

when $\hat{d}_{net}(t) \approx d_{net}(t)$. Since the CDOB is constructed without using the delay information, the method is robust against delay time uncertainty. However, the performance can be easily degraded under external disturbances or parameter uncertainties.

Proposed method: To improve the robustness of delay compensators against external disturbances as well as uncertainties on parameters including delay time information, this Letter incorporates a disturbance observer on the slave side. The configuration of the proposed controller is depicted in Fig. 2. The control input $v_s(t)$ is composed of the delayed input $v_m(t - T_1)$ from the master side and the disturbance estimation on the slave side. For the controller $C(s)$, a proportional–integral (PI) controller is used in the following section.

When ω^* is the speed reference, the control input $v_s(t)$ is given by

$$v_s(t) = v_m(t - T_1) + \hat{d}(t) \tag{13a}$$

$$v_m(t) = \frac{\omega_c \tau_n}{k_n}(\omega^* - \omega_p) + \frac{\omega_c}{k_n}\int_0^t (\omega^* - \omega_p)\,d\tau \tag{13b}$$

where $\omega_p(t) = \omega_m(t) + \omega_{cdob}(t)$ and ω_c is the closed-loop bandwidth.

To estimate the disturbance, the system is described by

$$\dot{z}_s(t) = Az_s(t) + Bv_s(t), \quad \omega_s(t) = Cz_s(t) \tag{14}$$

where $z_s = \begin{bmatrix}\omega_s & d\end{bmatrix}^T$ and the matrices are the same as (10). From (14), the disturbance observer is given by

$$\dot{\hat{z}}_s(t) = A\hat{z}_s(t) + Bv_s(t) + L_s\{\omega_s(t) - \hat{\omega}_s(t)\} \tag{15}$$

where $\hat{z}_s = \begin{bmatrix}\hat{\omega}_s & \hat{d}\end{bmatrix}^T$. As the eigenvalues of $(A - L_sC)$ are placed at the far left-half complex plane, $\hat{d}(t)$ converges to the uncertainty as follows:

$$\hat{d}(t) \to \alpha T_L + \frac{1}{k}\left(1 - \frac{\tau}{\tau_n}\right)x(t) + \left(\frac{k_n}{k}\frac{\tau}{\tau_n} - 1\right)v_m(t - T_1).$$

This implies that system (1) is rendered to behave like the following nominal system by using (13) with (15):

$$\dot{\omega}_s(t) = -\frac{1}{\tau_n}\omega_s(t) + \frac{k_n}{\tau_n}v_m(t - T_1). \tag{16}$$

This property can be proved by using the singular perturbation theory [4, 5]. Without uncertainty, the time delay can be compensated effectively with $\omega_p(t)$ from the CDOB.

Comparative experiments: Both computer simulations and experiments have been performed to test the effectiveness of the proposed method. The testbed system is a one-link manipulator driven by a DC motor. The load torque by the link can be represented by

$$T_L = J_L\dot{\omega}_s(t) + B_L\omega_s(t) \tag{17}$$

where J_L and B_L represent the load inertia and the frictional coefficient, respectively. In addition, an external step disturbance is enforced at 1 s. The control system parameters are given in Table 1. The nominal delay times for Smith predictor are denoted by T_{1n} and T_{2n}. The speed reference $\omega^* = 50$ rad/s and the closed-loop bandwidth $\omega_c = 50$ rad/s. All the eigenvalues of the CDOB (10) and the disturbance observer (15) are located at $s = -1000$.

Table 1: Control system parameters

k_n	35.9346	τ_n	0.0058
J_L	120 g-cm^2	B_L	0.0031 m Nm/(rad/s)
T_{1n}, T_{2n}	0.01 s	d	1 V

Fig. 3 illustrates the results of simulations (left column) and experiments (right column). The results compare the controlled output ω_s by using Smith predictor (SP), CDOB and the proposed method (Prop.). Three different time delays ($T = 0.02$, 0.04, 0.06) have been considered when $T_1 = T_2$ in the cases. When the real delay time $T = 0.06$, results with SP show unstable responses. The CDOB exhibits better performances than SP under the delay time uncertainty, but the performance deteriorates under parametric uncertainties and the additional disturbance. The proposed method shows improved performances compared to the previous schemes.

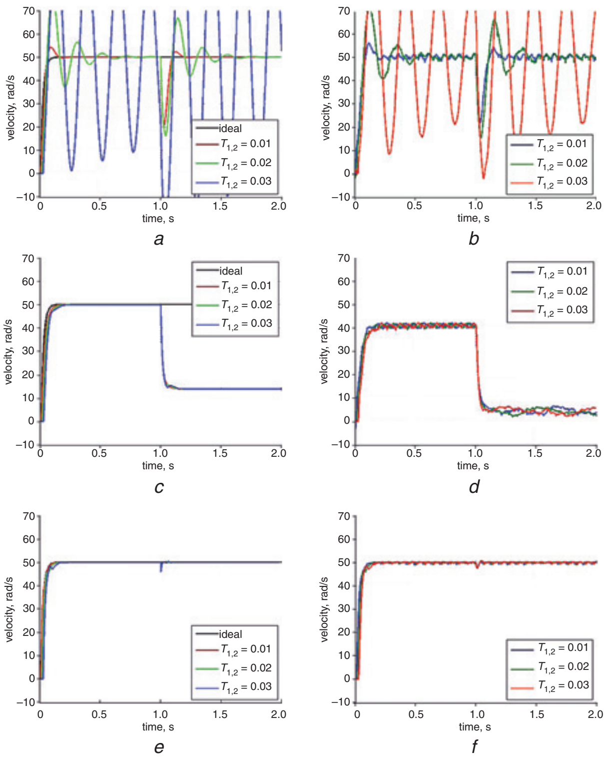

Fig. 3 *Comparative experimental results*

a ω_s (SP) (sim.)
b ω_s (SP) (exp.)
c ω_s (CDOB) (sim.)
d ω_s (CDOB) (exp.)
e ω_s (prop.) (sim.)
f ω_s (prop.) (sim.)

Conclusion: To cope with the performance degradation due to time delays, the use of delay compensators has been an important issue in various control applications. This Letter has investigated two well-known delay compensators as a prediction signal generator to obtain the closed-loop stability. For improving the robustness against delay time uncertainty as well as plant uncertainties including external disturbances, a disturbance observer has been incorporated with the CDOB on the slave side of the system. Through comparative simulations and experiments with a one-link manipulator, the effectiveness of the proposed method has been validated under uncertain time delay information and an external disturbance. The approach is not limited to the DC motor control system.

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