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Disturbance-Observer-Based Global Sliding Mode Controller for Electro-Hydraulic System

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Abstract

In order to improve the system performance affected by the model uncertainties and loading moments, a robust tracking controller is proposed for electro-hydraulic servo system. Considering the conventional disturbance observer (DOB) lacks the enough ability in estimating the whole disturbances in electro-hydraulic servo system, one global sliding mode controller (GSMC) is proposed based on the inner-loop DOB. The GSMC not only suppresses the remainder disturbances which cannot be observed by DOB, but also realizes the position tracking of electro-hydraulic servo system. Simulation results present that, compared with other traditional control schemes, the proposed robust control scheme can ensure electro-hydraulic servo system possess higher tracking precision. Moreover, there is no obvious high-frequency chattering at control input, therefore it also possesses higher application value.

Keywords*: Disturbance observer; electro-hydraulic system; sliding mode controller; robustness, tracking control*

1. Introduction

Electro-hydraulic technique organically combines electric and hydraulic characteristics, and then synthesizes the advantages of them. It not only possesses the capability of fast and accurate respond, but also drives the large inertia devices and then realizes the high power output. As a result, electro-hydraulic servo system has been widely used in many devices, *e.g.,* aerospace devices [1], mining, power and mobile devices in the fields of automatic control [2]. In fact, the presence of model uncertainties and loading torques brings a significant decline to the performance of electric-hydraulic servo control system. The traditional linear control methods, *e.g.,* PID control, are difficult to meet the performance requirements of modern process environment. Subsequently, it is necessary to search for new control approaches for electro-hydraulic servo system.

Disturbance observer (DOB) [3] is an effective control method to solve the above-mentioned problem, Furthermore, it is easy to be realized in practical applications. DOB can effectively improve the robust property of servo control system against the loading torque disturbances and the parameter perturbations in a small range, therefore it has get a wide range of applications [4-5]. As a result, we will introduce DOB to construct the robust controller of electric-hydraulic servo system. However, DOB cannot fully estimate the current value of equivalent disturbances, moreover, the remainder disturbances, which cannot be estimated by DOB, will also affect the performance of electro-hydraulic servo control system.

Sliding mode control (SMC) [6] has strong robustness with respect to parameter perturbations and external disturbances, therefore it has received a great deal of attentions and a wide range of applications [7-8]. In particular, a global sliding mode control (GSMC) method initially makes the system trajectory on the sliding mode surface by constructing the nonlinear switching function, which eliminates the initial reaching time to sliding mode surface, therefore GSMC has caused extensive researches [9-10]. However, the high-frequency chattering at control input is a major factor to restrict SMC being applied in practical applications. In this paper, we construct a control system with two-loop structure.

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That is, take DOB as an inner controller to estimate the most disturbances in control system, and then take GSMC as an outer controller to realize the servo tracking and also to suppress the remainder disturbances. This above-mentioned control structure can weaken the intense chattering to a some extent.

2. Problem Description

In general, electro-hydraulic servo control system is mainly composed by servo controller, power amplifier, servo valve, hydraulic cylinder, piston, potentiometer. Let r and y respectively denote the command input and the actual output of electro-hydraulic servo control system, meanwhile u denote the output of servo controller. In fact, the electro-hydraulic servo plant of single channel can be mathematically expressed by [2]:

$$G_P(s) = \frac{Y(s)}{U(s)} = \frac{K_a}{s(\frac{s^2}{\omega_h^2} + 2\frac{\xi_h}{\omega_h}s + 1)} \tag{1}$$

where ω_h is the natural frequency of hydraulic pressure, ξ_h is the damping coefficient of hydraulic pressure, K_a is the amplified coefficient of the electro-hydraulic servo plant.

When the electro-hydraulic servo control system is studied, except to care the properties of servo plant, we should also pay attention to the impact of loading torques on control system performance. The loading torques suffered from electro-hydraulic servo plant mainly includes the inertia moment T_J, the coulomb friction torque T_f, the damping torque T_d and the position torque T_p, the expressions of which converted to hydraulic axis are shown as follows.

$$\begin{cases} T_J = J\dfrac{\mathrm{d}^2 y}{\mathrm{d}t^2} \\ T_f = M_{f0}\mathrm{sgn}\left(\dfrac{\mathrm{d}y}{\mathrm{d}t}\right) \\ T_d = K_d\dfrac{\mathrm{d}y}{\mathrm{d}t} \\ T_p = K_p y \end{cases} \tag{2}$$

Where, J, M_{f0}, K_d and K_p denote the corresponding torque coefficients, which are converted to the hydraulic axis.

3. Robust Controller Design

3.1. DOB Design

The basic idea of DOB is to estimate the current equivalent disturbances by measuring the errors between the current output of actual system and that of nominal model. Then, it introduces the same amount of compensation into the control input, which can realize the strong suppression against the equivalent disturbances. The principle diagram of DOB is illustrated in Figure 1.

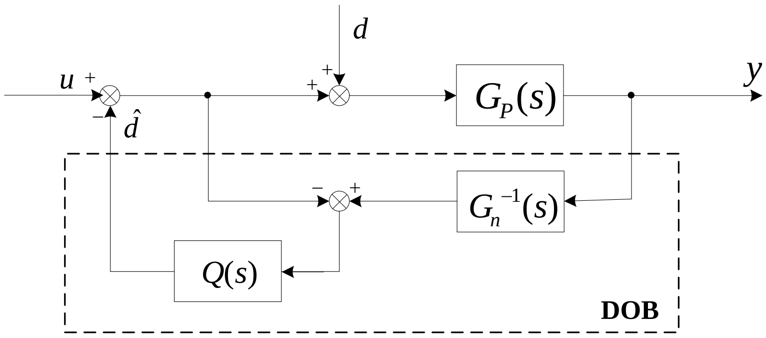

Figure 1. The Principle Diagram of DOB

In Figure 1, $G_n(s)$ denotes the nominal model of control plant, $Q(s)$ denotes a low pass filter, d and $\hat{d}$ represent the equivalent disturbances and the estimated disturbances respectively.

Regarding u and d as system inputs, then the system output can be obtained by using the superposition principle.

$$y = G_{UY}(s)u + G_{DY}(s)d \tag{3}$$

where,

$$G_{UY}(s) = \frac{G_P(s)G_n(s)}{G_n(s) + [G_P(s) - G_n(s)]Q(s)} \tag{4}$$

$$G_{DY}(s) = \frac{G_P(s)G_n(s)[1 - Q(s)]}{G_n(s) + [G_P(s) - G_n(s)]Q(s)} \tag{5}$$

Assume the bandwidth of low pass filter $Q(s)$ is f_0 (Hz), therefore there is $Q(s) \approx 1$ when frequency $f \le f_0$. As a result, $G_{UY}(s) \approx G_n(s)$ and $G_{DY}(s) \approx 0$ are established, which indicates that DOB can make the characteristic of control system be approximately equal to that of nominal model in low frequencies. That is, DOB has strong inhibitory effect on the external disturbances and parameter perturbations. Furthermore, we can achieve the compromise between disturbance suppression and robust stability of control system by choosing $G_n(s)$ and designing $Q(s)$.

In the selection of $G_n(s)$, we ignore the impact of the distortion of electro-hydraulic shaft, un-modeled dynamics and other factors, which can be treated as the unstructured uncertainties. Therefore, we can choose the nominal model of servo plant in single channel:

$$G_n(s) = \frac{K_{an}}{s\left(\frac{s^2}{\omega_{hn}^2} + 2\frac{\xi_{hn}}{\omega_{hn}}s + 1\right)} \tag{6}$$

where K_{an}, ω_{hn} and ξ_{hn} are nominal parameters.

The design of $Q(s)$ is quite important in the design of DOB. Firstly, in order to make $Q(s)G_n^{-1}(s)$ regular, the relative degree of $Q(s)$ should not be smaller than that of $G_n^{-1}(s)$. Aiming at the nominal model (6), we can design the corresponding filter as follows.

$$Q(s) = \frac{4\tau s + 1}{\tau^4 s^4 + 4\tau^3 s^3 + 6\tau^2 s^2 + 4\tau s + 1} \tag{7}$$

where parameter τ is positive.

The second point is the bandwidth design of $Q(s)$. Because parameter τ determines the bandwidth of $Q(s)$, we can achieve the compromise between the robust stability of inner-loop system and the disturbance rejection capability by choosing τ. When $f \le f_0$, there is $G_{UY}(s) \approx G_n(s)$, which will be the main basis for designing the outer-loop SMC.

3.2. GSMC Design

In order to achieve the angular position tracking of electro-hydraulic servo system, we will design an outer-loop GSMC based on the former designed inner-loop DOB. The GSMC can also deal with the disturbances which cannot be estimated by DOB. For the sake of the convenient design and analysis, the control system from input u to output y can be expressed by the state-space model:

$$\dot{\mathbf{x}} = \mathbf{A}_n \mathbf{x} + \mathbf{b}_n (u + \tilde{d}) \tag{8}$$

where, $\mathbf{x}=[y \quad \dot{y} \quad \ddot{y}]^{\mathrm{T}}$ denotes the state vector, $\tilde{d} = d - \hat{d}$ denotes the disturbances which cannot be estimated by DOB, and

$$\mathbf{A}_n = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_{hn}^2 & -2\xi_{hn}\omega_{hn} \end{bmatrix}, \quad \mathbf{b}_n = \begin{bmatrix} 0 \\ 0 \\ K_{an}\omega_{hn}^2 \end{bmatrix}.$$

According to system (8), we choose the following integral switching function:

$$s(t) = \mathbf{c}\left[\mathbf{x}_e(t) - \mathbf{x}_e(0)\right] - \mathbf{c}(\mathbf{A}_n - \mathbf{b}_n\mathbf{k})\int_0^t \mathbf{x}_e(\tau)\mathrm{d}\tau, \ \mathbf{x}_e = \mathbf{x}_d - \mathbf{x}, \ \mathbf{c}=[c_1 > 0 \quad 1] \tag{9}$$

where, $\mathbf{x}_d=[y_d \quad \dot{y}_d \quad \ddot{y}_d]^{\mathrm{T}}$ represents the desired state vector, $\mathbf{x}_e$ represents the state error vector, and $\mathbf{k}$ represents the feedback gain vector. From (9), we can get $s(0) = 0$ at the initial time, which indicates that the initial system trajectory is set on the sliding mode surface and then the initial time of arrival is eliminated.

Next, we can design the outer-loop GSMC according to the following theorem.

Theorem 1 For system (8), choosing switching function (9), the control law of GSMC is designed as follows:

$$u = \mathbf{k}\mathbf{x}_e + q\,\mathrm{sgn}(s) + \mathbf{f}\dot{\mathbf{x}}_d, \ \mathbf{f} = \begin{bmatrix} \dfrac{1}{K_{an}} & \dfrac{2\xi_{hn}}{K_{an}\omega_{hn}} & \dfrac{1}{K_{an}\omega_{hn}^2} \end{bmatrix} \tag{10}$$

If the following two conditions are satisfied,

(1)The eigenvalues of $\mathbf{A}_n - \mathbf{b}_n\mathbf{k}$ possess negative real parts;

(2) $q > \left|\tilde{d}\right|$.

The robust state tracking of system (8) will be realized, *i.e.*, $\mathbf{x} \to \mathbf{x}_d$.

Proof: We select the Lyapunov function as follows:

$$V = \frac{1}{2}s^2 \tag{11}$$

To differential the two sides of Eq. (11) about time, we can obtain:

$$\dot{V} = s\dot{s} = s\left[\mathbf{c}\dot{\mathbf{x}}_e - \mathbf{c}(\mathbf{A}_n - \mathbf{b}_n\mathbf{k})\mathbf{x}_e\right] \tag{12}$$

To make variable transformation, we can convert system (8) into the system which takes $\mathbf{x}_e$ as the state vector, that is:

$$\dot{\mathbf{x}}_e = \mathbf{A}_n\mathbf{x}_e + \mathbf{b}_n(u_1 + \tilde{d}_1) \tag{13}$$

where,

$$u_1 = -u + \mathbf{f}\dot{\mathbf{x}}_d \,,\; \tilde{d}_1 = -\tilde{d} \tag{14}$$

Then, substituting (13) into (12) can obtain:

$$\begin{aligned} \dot{V} &= s\left[\mathbf{c}\left(\mathbf{A}_n\mathbf{x}_e + \mathbf{b}_n u_1 + \mathbf{b}_n\tilde{d}_1\right) - \mathbf{c}(\mathbf{A}_n - \mathbf{b}_n\mathbf{k})\mathbf{x}_e\right] \\ &= -\mathbf{c}\mathbf{b}_n \left|s\right|\left[q - \tilde{d}_1 \operatorname{sgn}(s)\right] \end{aligned} \tag{15}$$

Thus, when condition (2) is met, $\dot{V} \le 0$ is established. Moreover, when and only when $s = 0$, there is $\dot{V} = 0$. Therefore, the reachability for sliding mode can be satisfied, namely the system trajectory trends to the designed sliding mode surface.

When the system trajectory is in the sliding mode stage, we can get:

$$\dot{\mathbf{s}} = \mathbf{c}\left(\mathbf{A}_n\mathbf{x}_e + \mathbf{b}_n u_1 + \mathbf{b}_n\tilde{d}_1\right) - \mathbf{c}(\mathbf{A}_n - \mathbf{b}_n\mathbf{k})\mathbf{x}_e = 0 \tag{16}$$

Then, the equivalent control is calculated by:

$$u_{1eq} = -\mathbf{k}\mathbf{x}_e - \tilde{d}_1 \tag{17}$$

Taking the equivalent control law (17) into system (13), we can obtain the expression of sliding mode motion as follows.

$$\dot{\mathbf{x}}_e = (\mathbf{A}_n - \mathbf{b}_n\mathbf{k})\mathbf{x}_e \tag{18}$$

At this time, when condition (1) is met, the sliding mode motion is convergent, that is $\mathbf{x}_e \to \mathbf{0}$.

According to the above-mentioned analysis, the total output of the electro-hydraulic servo controller is:

$$v = u - \hat{d} \tag{19}$$

4. Simulation Results

In this section, the numerical simulations of traditional PID and PID+DOB control schemes are compared with those of the proposed control scheme (*i.e.*, GSMC+DOB control scheme), in order to obtain the performance benefits of the proposed control scheme.

In the simulation, the actual plant parameters are $K_a = 18.5$, $\omega_h = 95.0$ rad/s and $\xi_h = 0.35$. Meanwhile, the nominal model parameters are chosen as $K_{an} = 18.0$, $\omega_{hn} = 100.0$ rad/s and $\xi_{hn} = 0.30$. It can be seen that there is modeling error between the nominal model and the actual plant. Moreover, the coefficients of loading moments are $J = 0.0001\,\mathrm{N \cdot s^2/rad}$, $M_{f0} = 3.0\,\mathrm{N}$, $K_d = 0.0020\,\mathrm{N \cdot s/rad}$ and $K_p = 0.010$ N/rad.

The parameters of PID control scheme are shown as: $k_p = 3.0$, $k_i = 0.01$, $k_d = 0.2$

The parameters of DOB+PID control scheme are shown as: $\tau = 0.015$ s/rad, $k_p = 3.0$, $k_i = 0.01$, $k_d = 0.2$

The parameters of DOB+GSMC control scheme are shown as: $\tau = 0.015$ s/rad, $\mathbf{c} = [2 \;\; 1 \;\; 1]$, $\mathbf{k} = [0.3162 \;\; 0.2207 \;\; 0.0997$, $q = 0.5$

The initial state vector of the electro-hydraulic servo system is set as [0.5 deg 0deg/s 0deg/s^2]^T, and the position tracking command is chosen as a sine signal with 10deg magnitude and 1Hz frequency, which is shown in Figure 2.

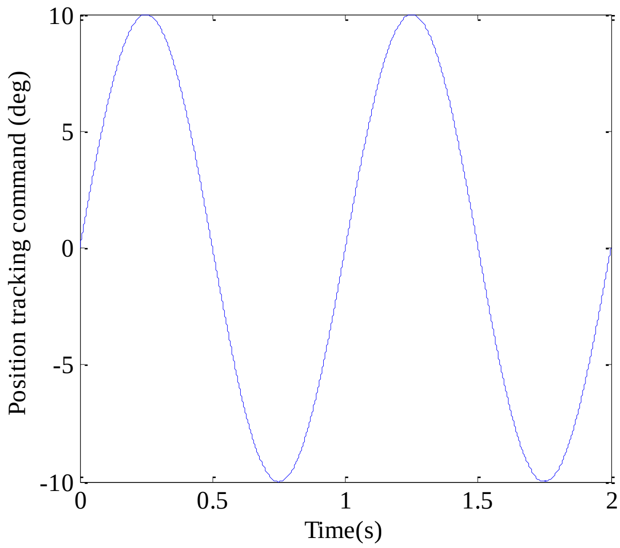

Figure 2. The Position Tracking Curve of Electro-Hydraulic Servo System

We contrast the proposed control scheme with conventional PID and PID+DOB control schemes, and then the tracking errors of the three control schemes are shown in Figure 3.

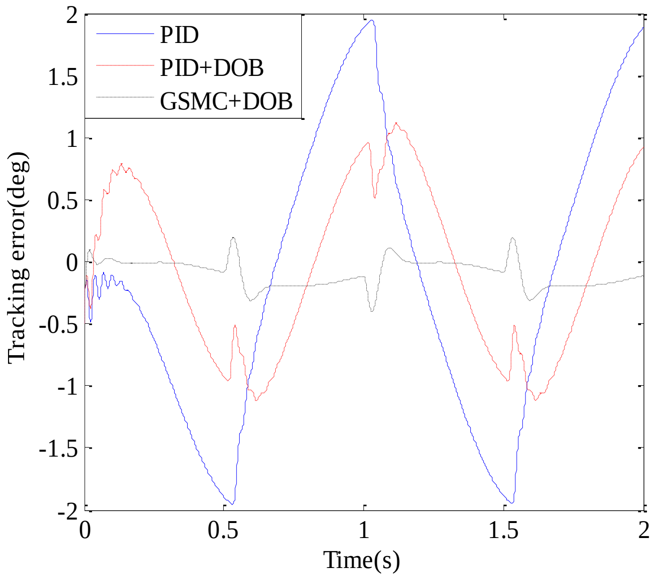

Figure 3. Tracking Error Curves of Electric-Hydraulic Servo System under the Three Control Schemes

As can be seen from Figure 3, compared with PID control scheme, the tracking errors of electro-hydraulic servo system are smaller by using PID+DOB control scheme, which indicates that the introduced DOB possesses robust property against equivalent disturbances. However, compared with PID+DOB control scheme, the tracking errors of electro-hydraulic servo system are further smaller by using GSMC+DOB control scheme, which reflects that the GSMC possesses the additional inhibitory effect on the un-estimated disturbances resulted from DOB, and then further improves the robustness of control system.

In addition, the curve of servo controller output under the proposed control scheme is shown in Figure 4.

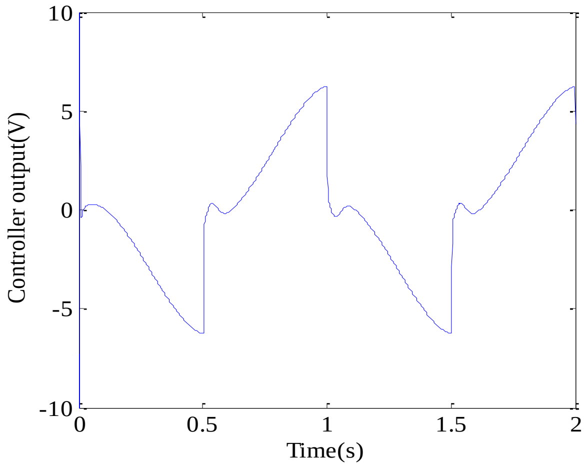

Figure 4. The Curve of Servo Controller Output under the Proposed Control Scheme

Seen from Figure 4, owing to the design of the double-loop control structure in this paper, there is no significant high-frequency chattering at controller output in the period of stable tracking.

5. Conclusions

From the simulation results, the robust control scheme proposed in this paper, which is constructed by the DOB in inner loop and the GSMC in outer loop, can realize the better tracking properties of electro-hydraulic servo system. The designed DOB can estimate the most unknown equivalent disturbances, which basically guarantees the robust property of electro-hydraulic servo control system with respect to system uncertainties, such as modeling errors and loading torque disturbances. The designed GSMC can realize the servo tracking and also deal with the remainder disturbances which cannot be estimated by DOB.

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