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Multi-channel synchronization control based on mean of deviation coupling control

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ABSTRACT

The development status of multi-channel synchronous control strategy is analyzed, and a new mean of deviation coupling control strategy based on the thought of the same given control and error compensation is presented, which can reduce complexity of the control structure with the increasing number of channels. The mathematical models of PMSM (Permanent Magnet Synchronous Motor) and load are established. The global stability and convergence of the control system have been proved according to Lyapunov stability theory. In this paper, mean of deviation coupling control strategy is applied to the synchronization control system of multi-channel, and compared with master-slave control strategy. The simulation results not only show the effectiveness of the proposed control approach, but also verify that the proposed control strategy is better than master-slave control strategy, which has better anti-interference and synchronous control performance.

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1. Introduction

With the continuous improvement of motor control technology, the previously complex mechanical structure to realize the motion control is now gradually replaced by motor drive, and the synchronous control system of multi-channel has been used widely in many industry fields recently, including microelectronics, aerospace, solar cell, and flat panel manufacturing and inspection [1–3]. As the motion control system requires higher reliability and control accuracy, the synchronous performance is very important in multi-channel synchronization control. At present, there are mainly two typical control schemes which is used in current industrial control systems for realizing multi-channel synchronous motion, one is the cascade synchronous control scheme, the other is the parallel synchronous control scheme [4].

In the cascade synchronous control scheme, which is also named master-slave control strategy [5,6]; one channel is assigned as the master and the other channels as the slaves. It has simple control structure, but the synchronous performance will be limited due to the servo lag of the master channel, which indicates that the position response of the slave channel will deviate from the given position command [4,7]. For remedying this problem, the parallel synchronous control scheme has been proposed, which consists of cross-coupling control [8–11] and relative coupling control [12,13]. Cross-coupling control strategy has been proposed in [14], which shares the feedback information of both control loops in bi-axis motion system, and the influences of load disturbance on system performance are reduced [15]. But it is difficult to extent this method for more than two channels [16]. In order to deal with this problem, relative coupling control strategy is preferred. Many reports had proved that it had indeed better synchronous control performance during the past years. But [17,18] points out that when the number of channel is increasing, the complexity of system control structure is also increasing, while the feedback law has become more and more difficult to obtain.

In order to ensure the synchronization performance of system and reduce complexity of control structure with the increasing number of channels, a new mean of deviation coupling control strategy, which is suitable for multi-channel, is presented in this paper.

The organization of the present paper is as follows. The mean of deviation coupling control strategy is presented in Section 2. The mathematical models of PMSM and load are introduced in Section 3. The stability analysis of mean of deviation coupling synchronization control system is presented in Section 4. Simulation results conducted on a three-channel system are given in Section 5. Section 6 gives the conclusion.

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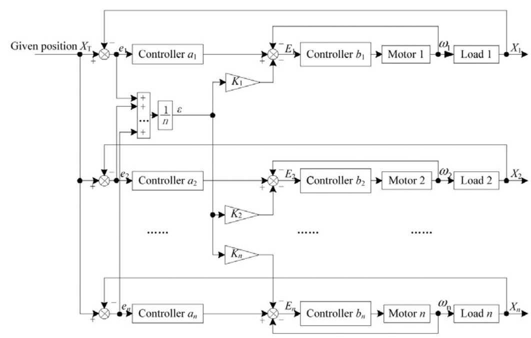

Fig. 1. Schematic diagram of the mean of deviation coupling strategy.

2. Mean of deviation coupling control strategy

The mean of deviation coupling control strategy is based on the thought of the same given control and error compensation. The schematic diagram of mean of deviation coupling control strategy is shown as Fig. 1. All channels can follow the given position X_T in this control method, and a good synchronization performance can be ensured during starting and stopping. The basic idea of the strategy is calculating the position tracking error between one channel's position and the given value, then averaging all the errors as the compensation signal for every channel.

Where n is the number of channels, e_i is the position tracking error of channel $i\,(1 \le i \le n)$, ε is mean value of the position tracking errors, E_i is speed tracking error of channel i, K_i is speed compensation gain, ω_i is the mechanical angular velocity of motor i, X_i is the position of channel i.

It can be seen from the schematic diagram that every channel has the same given signal, which avoids shortcomings of master-slave control strategy. Because the idea of the proposed control strategy is just to calculate position tracking errors and their average, the complexity of system control structure and compensator is not changing with the increasing number of channels.

3. Mathematical models of PMSM and load

3.1. The mathematical model of PMSM

PMSM has been chosen as plant, and control scheme is $i_d = 0$. The mathematical model in $d-q$ coordinate is as follows [19,20].

The equation of the flux linkage and voltage can be described as

$$\begin{cases} \psi_d = \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{1}$$

$$u_q = L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} + p\omega\psi_f + R_s i_q \tag{2}$$

The equation of electromagnetic torque is stated as

$$T_e = \frac{3}{2} p \psi_f i_q. \tag{3}$$

The equation of mechanical motion is presented as

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = T_e - T_L - B\omega. \tag{4}$$

The relationship between motor angular velocity ω and angle θ is $\omega = \mathrm{d}\theta/\mathrm{d}t$, so the equation is given as follows

$$\theta(S) = \frac{1}{S}\omega(S) \tag{5}$$

where u_q is q-axis stator voltage, i_q is q-axis stator current, ψ_d and ψ_q are d-axis and q-axis stator fluxes, respectively; L_q is q-axis stator inductance, R_S is stator resistance, ψ_f is rotor flux, T_e is electromagnetic torque of motor, T_L is load torque, J is moment of inertia, B is friction coefficient, p is number of pole pairs.

3.2. Load model

The load is composed of servo motor, reduction gear, ballscrew and stage. The transfer function of load model can be simply described as follows

$$G_L(S) = \frac{X(S)}{\theta(S)} = \frac{S_0}{2\pi h} = K_T \tag{6}$$

where X is the position of stage, S_0 is the ballscrew lead, h is gear reduction ratio.

4. Theoretical researches on stability and convergence of mean of deviation coupling control system

In the following sections, the symbols with subscript i and j denote corresponding variables and parameters of channel i and j, respectively.

The design idea of controller is to want the speed tracking error to converge to zero in a progressive manner. The following modifications have been made according to (3)–(6).

$$\ddot{X} = -\frac{B}{J}\dot{X} + \frac{3K_T p\psi_f}{2J} i_q - \frac{K_T}{J} T_L \tag{7}$$

The equation of motion of the ith-channel can be rewritten as

$$\ddot{X}_i = -\frac{B_i}{J_i}\dot{X}_i + \frac{3K_{T(i)} p \psi_{f(i)}}{2J_i} i_{q(i)} - \frac{K_{T(i)}}{J_i} T_{L(i)} \tag{8}$$

Set $f_i = \left(\left(3K_{T(i)} p \psi_{f(i)}\right)/2J_i\right) i_{q(i)} - \left(K_{T(i)}/J_i\right) T_{L(i)}$, $b_i = B_i/J_i$, Eq. (8) can be changed as follows

$$\ddot{X}_i = f_i - b_i \dot{X}_i \tag{9}$$

The position tracking error of the ith-channel is as follows

$$e_i = X_T - X_i \tag{10}$$

The mean value of position tracking errors for all channels is defined as follows

$$\varepsilon = \frac{\sum_{i=1}^{n}(X_T - X_i)}{n} = X_T - \frac{\sum_{i=1}^{n} X_i}{n}. \tag{11}$$

The speed tracking error of the ith channel after compensating is as follows

$$E_i = a_i e_i - K_i \varepsilon - \frac{\dot{X}_i}{K_{T(i)}}. \tag{12}$$

For the nonlinear differential equations, a Lyapunov function can be constructed according to Lyapunov's second method [21]. The stability of the system can be determined by researching the positive definiteness of the function and negative definiteness or negative semi-definite of its total derivative.

We take the ith channel as an example in judging. If we want E_i to converge to zero, it can be assumed that we have the Lyapunov function

$$V_i = E_i^2 \tag{13}$$

where $V_i > 0$.

If $\dot{E}_i = -c_i E_i$, then

$$\dot{V}_i = 2E_i\dot{E}_i = -2c_i E_i^2 < 0 \tag{14}$$

where $c_i > 0$.

Therefore, when the tracking error E_i asymptotically converges to zero, the system is globally asymptotically stable.

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