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Application of CMAC Neural Network Coupled with Active Disturbance Rejection Control Strategy on Three-motor Synchronization Control System

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Abstract: Three-motor synchronous coordination system is a MI-MO nonlinear and complex control system. And it often works in poor working condition. Advanced control strategies are required to improve the control performance of the system and to achieve the decoupling between main motor speed and tension. Cerebellar Model Articulation Controller coupled with Active Disturbance Rejection Control (CMAC-ADRC) control strategy is proposed. The speed of the main motor and tensions between two motors is decoupled by extended state observer (ESO) in ADRC. ESO in ADRC is used to compensate internal and external disturbances of the system online. And the anti interference of the system is improved by ESO. And the same time the control model is optimized. Feedforward control is implemented by the adoption of CMAC neural network controller. And control precision of the system is improved in reason of CMAC. The overshoot of the system can be reduced without affecting the dynamic response of the system by the use of CMAC-ADRC. The simulation results show that: the CMAC-ADRC control strategy is better than the traditional PID control strategy. And CMAC-ADRC control strategy can achieve the decoupling between speed and tension. The control system using CMAC-ADRC have strong anti-interference ability and small regulate time and small overshoot. The magnitude of the system response incited by the interference using CMAC-ADRC is smaller than the system using conventional PID control 6.43 %. And the recovery time of the system with CMAC-ADRC is shorter than the system with traditional PID control 0.18 seconds. And the triangular wave tracking error of the system with CMAC-ADRC is smaller than the system with conventional PID control 0.24 rad/min. Thus the CMAC-ADRC control strategy is a good control strategy and is able to fit three-motor synchronous coordinated control. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Cerebellar model, Active Disturbance Rejection Control, Decoupling ability, Feedback, Anti-interference.

1. Introduction

Three-motor synchronous system is a MI-MO, nonlinear complex systems, widely used in the field of industrial control [1]. The performance of three synchronous motor coordination is directly affected by the decoupling of the motor speed and the belt tension, anti-interference ability and tracking accuracy [2]. The control method of the traditional PID is simple, and the control parameters of the traditional are fixed. Thus the traditional PID control method is difficult to adapt to complex and changing control environment. In recent years, many scholars are making extensive and in-depth research for two motors, three motor coordination as well as multi-motor synchronous control, and propounding some control strategies.

The sliding mode and variable structure control algorithm is applied to the multi-motor synchronous control in literature [3]. In literature [4], the neural network generalized inverse internal model control is applied to the synchronous control of two motors. And the neural network is applied to approximate generalized inverse model. The model and the original system make the pseudo-complex system that combines the internal model control to achieve decoupling of the speed and tension. In the 1990s, based on the traditional feedback control theory Chinese Academy of Sciences researcher Han Jing-qing first proposed the theory of ADRC and achieved good control effect. Domestic and foreign scholars have studied and applied to the multi-motor synchronized control. In literature [5], a first-order ADRC synchronization control strategy aiming at multiple motors synchronized control is presented, and the extended state observer (ESO) is used to achieve decoupling of speed and tension; in literature [6], based on the first order ADRC the second order ADRC technology is used to improve the control performance of the system; Literature [7] puts forward fuzzy ADRC control strategy to resolve the difficulties in the ADRC control parameters adjustment. And fuzzy control technology is applied to adjust the parameters neatly. In literature [8], the combining of least squares support vector machine and ADRC is applied to two motor synchronization control.

CMAC can overcome the shortcomings of the conventional BP network such as slow learning, poor real-time. CMAC is a real-time control strategy which is more suitable for nonlinear system than general BP neural network [9]. And CMAC has a certain generalization ability, simple structure, a small amount of computation, faster learning [10-12]. I make CMAC couple with ADRC based on the basis of previous studies. The decoupling of speed and tension is finished by the use of ADRC. The control system has strong anti-interference ability and robustness. And the sum disturbance can be compensated online by the use of ADRC. CMAC can study online, inhibit multi-motor synchronous system overshoot, and improve the dynamic performance of the system. Through a large number of simulations and experiments show that CMAC-ADRC is a feasible control method in the field of multi-motor synchronous controlling with good control effect.

2. Three-motor Synchronous Control System Mathematical Model

Control object of the system is three motors driven by three 220 V AC inverters. And three motors are connected via belts. The specific hardware model is shown in Fig. 1.

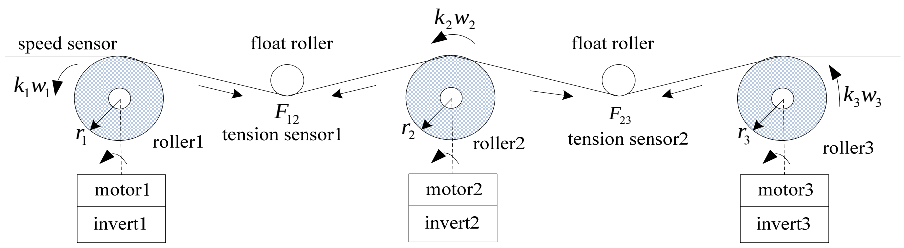


Fig. 1. The three-motor synchronous system hardware model.

According to Hooke's law, we get:

$$\begin{cases} \dot{F}_{12} = \dfrac{K_1}{T_1}\left(\dfrac{1}{n_{p1}} r_1 k_1 \omega_{r1} - \dfrac{1}{n_{p2}} r_2 k_2 \omega_{r2}\right) - \dfrac{F_{12}}{T_1} \\ \dot{F}_{23} = \dfrac{K_2}{T_2}\left(\dfrac{1}{n_{p2}} r_2 k_2 \omega_{r2} - \dfrac{1}{n_{p3}} r_3 k_3 \omega_{r3}\right) - \dfrac{F_{23}}{T_2} \end{cases}, \quad (1)$$

where F_{12} is the belt tension between main motor 1 and motor 2; F_{23} is the belt tension between motor 2 and motor 3; ω_{r1}, ω_{r2} and ω_{r3} are the rotor electrical angular velocities of three motors; T_1, T_2 are the time constants of the belt tension; r_1, r_2 and r_3 are the radius of the three rollers; k_1, k_2 and k_3 are the motor speed ratios between the three motors; n_{p1}, n_{p2} and n_{p3} are the numbers of pole pairs.

3. CMAC-ADRC Control Strategy

3.1. The Overall Structure of Control System

Control system is formed with CMAC-ADRC controller and three-motor synchronous system. The specific structure is shown in Fig. 2.

3.2. ADRC Control Algorithm

ADRC (ARDC) usually consists of tracking differentiator (TD), extended state observer (ESO), non-linear error feedback (NLSEF) and disturbance compensation [13]. The main role of TD is to arrange

TD transition process. The system uses the first-order ARDC and second-order ESO which has no differential term. Thus TD is canceled. And the disturbance is measured and compensated by the use of ESO. In order to enhance system performance in real time and reduce the amount of calculation, NLSEF is instead of the traditional PD control in ADRC.

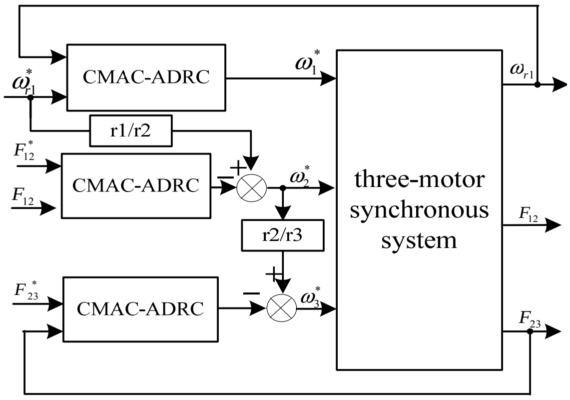


Fig. 2. The overall structure of the control system.

The model of the control system can be written as:

$$\begin{aligned} x^{(n)} &= a_0(x^{(0)}, x^{(1)}, \ldots, x^{(n-1)}, t) + b_0 u \\ &+ a_1(x^{(0)}, x^{(1)}, \ldots, x^{(n-1)}, w(t)) + b_1 u \end{aligned} \quad (2)$$

where $a_0(x^{(0)}, x^{(1)}, ..., x^{(n-1)}, t) + b_0 u$ is the know part; $a_1(x^{(0)}, x^{(1)}, ..., x^{(n-1)}, w(t)) + b_1 u$ is the unknown part.

ESO does not rely on a specific mathematical model. According to the input signals and the feedback output signals, ESO extends the sum disturbance to the extra state and compensates it into the system directly. Thus ADRC can decouple the speed and tension with a strong anti-jamming capability. The specific design algorithm is shown in the following equation.

$$\begin{cases} e_1 = z_1 - y \\ \dot{z}_1 = z_1 + h(z_2 - \beta_{01} e + b_0 u) \\ \dot{z}_2 = z_2 - h\beta_{02}\, fal(e_1, \alpha, \delta) \end{cases}, \quad (3)$$

where e_1 is the observation error; z_1 is the tracking signal of output feedback signal named y; z_2 is the observation of sum of the system disturbances, h is the sampling time the control system; b_0 is the compensation factor of ADRC; β_{01} and β_{02} are the error correction gains of the output signal; *fal* is the power function; δ is the linear space.
Control structure is shown in Fig. 3.

The sum control input is:

$$u_p = u_0 + z_2 / b_0 \quad (4)$$

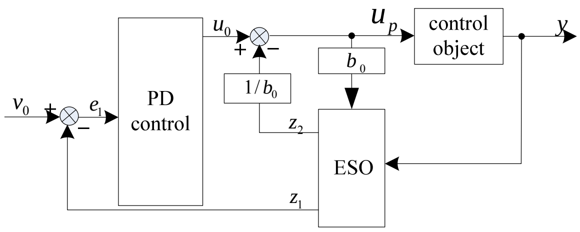


Fig. 3. ADRC control structure.

3.3. ADRC-CMAC Control

CMAC neural network is based on the local learning neural network. CMAC is capable of learning any multidimensional nonlinear mapping and typically used for feedforward and feedback as well as direct inverse motion control. The control system uses CMAC coupling with ADRC for three-motor synchronous control system.

Composite structure is shown in Fig. 4. CMAC is mainly used to achieve feedforward control and inverse dynamics model of the controlled object, to improve the control accuracy of the system. Simple ADRC often generate a certain overshoot at startup, While CMAC can suppress the overshoot without affecting the system dynamic performance. ADRC achieves mainly feedback control. ADRC uses ESO for achievements of observations online, compensates the internal and external disturbance into the system, improves anti-jamming capability of the system and ensures the stability of the system.

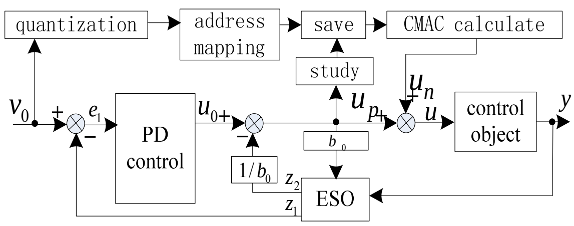


Fig. 4. ADRC-CMAC structure.

CMAC adopts supervised learning algorithm [14]. The corresponding CMAC output $u_n(k)$ is calculated and compared with the controller input $u(k)$ in the end of each control period. And then CMAC corrects weights into the learning process. CMAC makes $u_n(k)$ and $u(k)$ closest through the study. The control algorithm of the system is shown as follows:

$$u_n(k) = \sum_{i=1}^{c} w_i a_i, \quad (5)$$

$$u(k) = u_n(k) + u_p(k), \quad (6)$$

where a_i is the binary sequence; c is the generalization parameter of CMAC network; $u_p(k)$ is the output of ADRC.

CMAC design is usually divided into three steps, namely to quantify (concept maps), address mapping (actual mapping), CMAC function calculation.

Corresponds to the system, firstly according to the literature [15] we can know:

$$v_i = \begin{cases} s\min, & 1 \le i \le C \\ v_{i-1} + \Delta v_i, & C+1 \le i \le C+N \\ s\max, & N+C+1 \le i \le N+2\times C \end{cases} \quad (7)$$

The input space S=[smin, smax] is divided into N+2C quantization interval, completed concept mapping, and then according to the follows:

$$a_i = \begin{cases} 1, & rin \ge v_i \ and \ rin \le v_{i+C} \\ 0, & others \end{cases} \quad (8)$$

CMAC performs the actual mapping to a_i . Finally CMAC function calculation is finished. CMAC adjusted quota is shown as follows:

$$E(\mathrm{k}) = 0.5(u(k) - u_n(k))^2 \times a_i / c, \quad (9)$$

$$\Delta w(k) = \eta \frac{u(k) - u_n(k)}{c} \times a_i = \eta \frac{u_p(k)}{c} \times a_i, \quad (10)$$

$$w(k) = w(k-1) + \Delta w(k) + \alpha(w(\mathrm{k}) - w(\mathrm{k}-1)), \quad (11)$$

where η indicates the network learning rate which lies in 0 to 1; α means that the amount of inertia which lies in 0 to 1.

4. Controller Parameter Tuning

Control parameter of the system includes β_{01} , β_{02} , b , k_p and k_d in ADRC, as well as the generalization parameter named C, quantization level named N, and learning rate named η in CMAC. According to the expanded state observer's numerical simulation indicates that β_{01} usually take inversely proportional to the step size h and β_{02} usually take inversely proportional to $1/3h^2$. The sampling step time of the system takes h =100 ms. Thus here β_{01} takes 10 and β_{02} takes 33. Extensive simulation studies show that the estimated demanding of b is less. And the control results can not be affected if the relative error is controlled within 30 %. b lies in 0 to 20. Here b takes 0.1. k_p as proportional adjustment coefficient is used to reduce bias, here selected 50. k_d is differential coefficient. And appropriate regulating k_d can reduce the adjust time, improve the response speed of the system and enhance dynamic performance of the system. Here k_d takes 0.1. The generalization parameter C is associated with the stability of the control system [16]. If C is increased, the stability of the system can be enhanced to a certain extent, but also increases the calculation time, real-time control is reduced, the efficiency of the control will drop. The corresponding stability of the control system is guaranteed by ADRC. Therefore generalization parameter C do not need to select too large. Here select 5.0. Quantization levels N have little effect on the system. According to the memory capacity and computing speed, N selects 100. Learning rate η affects the system steady-state accuracy and response speed. If η takes greater, the respond becomes faster, steady-state error becomes bigger, mapping accuracy becomes lower. Otherwise, if η takes smaller, the respond becomes slower, steady-state error becomes smaller, mapping accuracy becomes higher [17]. Considering that the ADRC control system has good fast performance, improving the tracking accuracy has become the main requirements of the system. Therefore, here $\eta = 0.1$.

5. Simulation and Research

The model of the system is designed using S function in Simulink environment. And motor control parameters are selected as follows:

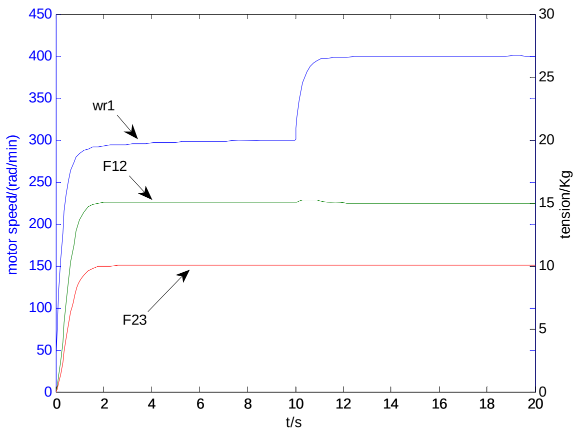
$$L_{r1} = L_{r2} = L_{r3} = 0.58; np1 = np2 = np3 = 2;$$
$$J_1 = J_2 = J_3 = 0.5; T_1 = T_2 = 1;$$
$$k_1 = k_2 = k_3 = \frac{1}{15}; r_1 = r_2 = r_3 = 0.09;$$
$$T_{r1} = T_{r2} = T_{r3} = 0.05; \psi_{r1} = \psi_{r2} = \psi_{r3} = 0.95$$

Simulation and analysis aiming at the decoupled nature, anti-jamming capability, tracking performance and other indicators of the system is finished.

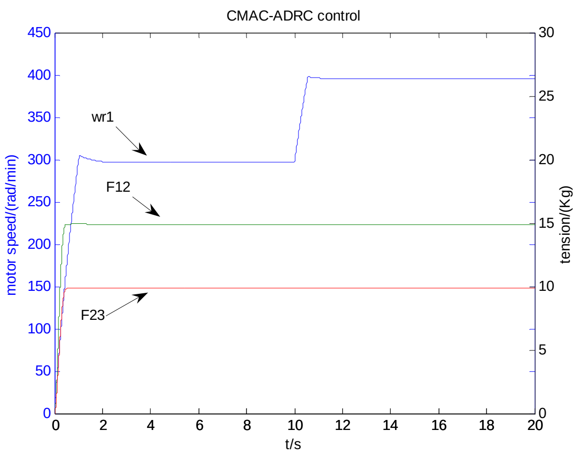
5.1. Simulation and Analysis of Decoupling Performance

The belt tension F_{12} between the first motor and the second motor is set to 15 kg. The belt tension F_{23} between the second and the third motor is set to 10 kg. The speed of the main motor changes suddenly in the time of 10 seconds. And the speed increases from 300 rad/min to 400 rad/min. Adopting two different control strategies to simulate the system, we get speed-tension response curve of PID control and CMAC-ADRC control, as shown in Fig. 5 (a) and (b).

From the control graph can be seen: to the traditional PID control mode, the belt tension between the first motor and the second motor F_{12} increased 2.2 kg when the main motor speed increases suddenly. However, to CMAC-ADRC control mode, the belt tension between the first motor and the second motor F_{12} increased 0.02 kg when the main motor speed increases suddenly. From here we can know the belt tension is little affected by the suddenly change of speed in the control mode of CMAC-ADRC. Thus CMAC-ADRC has good decoupling effect of speed and tension. Look from the system response speed, dynamic response speed of CMAC-ADRC control system is better than the traditional PID control. And CMAC-ADRC control system have many advantages such as small overshoot, short settling time, and so on.



(a) PID control



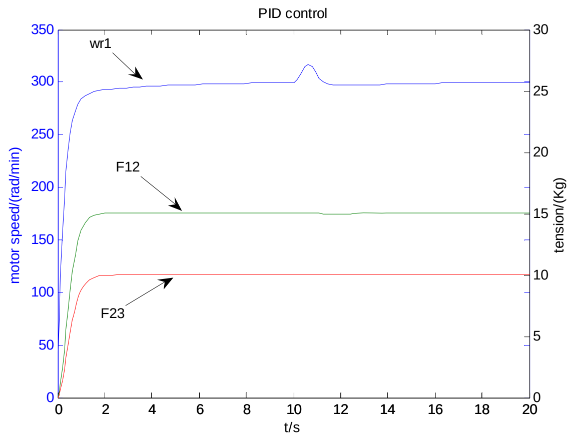
(b) CMAC-ADRC control

Fig. 5. The speed-tension curve of the motors when tension is set and speed increases suddenly.

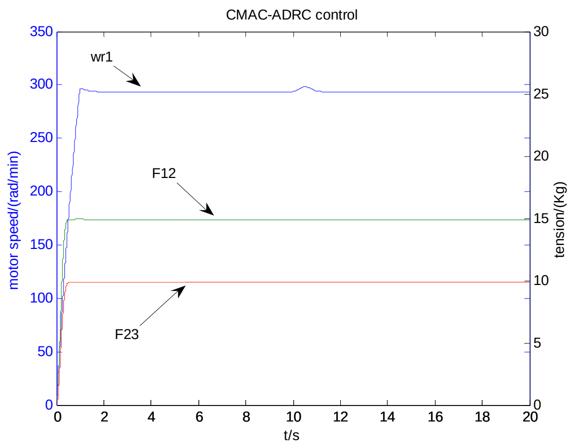
5.2. Simulation and Analysis of Anti-interference Performance

The main motor speed is set to 300 rad/min. And the simulation test spends 20 seconds. The interference signal is triangular wave which amplitude is 300 rad/min and pulse width is 1 second. For the traditional PID control and CMAC-ADRC control, we get anti-interference performance curves through simulation, as shown in Fig. 6 (a) and (b).

If the PID control strategy is adopted, the system response amplitude generated by interference 22 rad/min which is 7.3 % of the system steady state velocity. And the recovery time is 1.2 seconds. However, if CMAC-ADRC control strategy is adopted, the system response amplitude generated by interference 2.8 rad/min which is 0.93 % of the system steady state velocity; And the recovery time is 1.02 seconds. Using CMAC-ADRC control strategy, system response amplitude generated by interference than conventional PID control small 6.43 %. And the same time recovery time saves 0.18 seconds.



(a) PID control



(b) CMAC-ADRC control

Fig. 6. Anti-interference performance test curves.

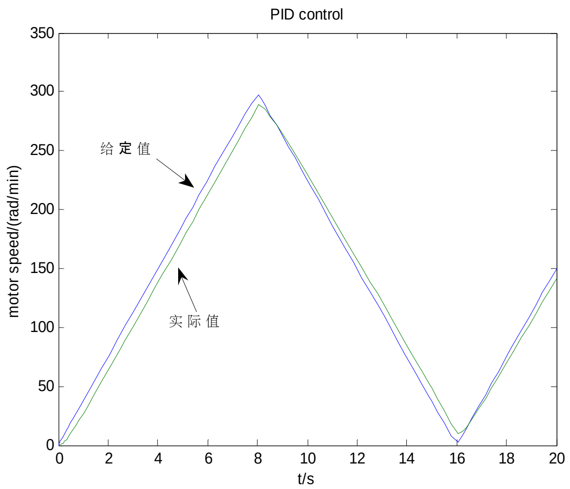
Thus it can be seen that CMAC-ADRC control strategy has good anti-jamming features, good dynamic response performance.

5.3. Simulation and Analysis of Tracking Performance

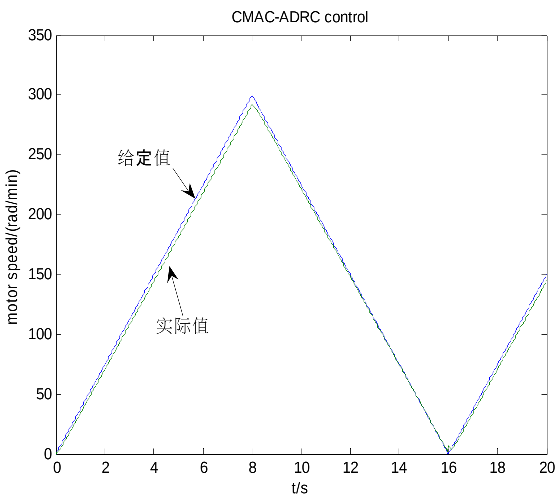
Triangular wave signal that peak value is 300 rad/min is made as the reference input signal of the main motor. The output of the system tracks the reference input signal. For 20 seconds simulation, we get tracking simulation curves adopting the traditional PID control and CMAC-ADRC control, as shown in Fig.7 (a) and (b).

As we can know from the tracking curves:

For the traditional PID control, the tracking error is under 0.4 rad/min; the tracking error is large when the speed is increasing. For CMAC-ADRC control, the tracking error is under 0.16 rad/min. And the tracking error of CMAC-ADRC is smaller 0.24 rad/min than the traditional PID control. Thus CMAC-ADRC control strategy has better tracking accuracy compared to conventional PID control.



(a) PID control



(b) CMAC-ADRC control

Fig. 7. Tracking test curves.

6. Conclusions

In this paper CMAC-ADRC control algorithm is studied. And simulation study is finished for three motor synchronous system model. The results showed that:

CMAC-ADRC control strategy can achieve decoupling of speed and tension in three motor system, strong anti-jamming capability, high tracking accuracy, good dynamic response, and small overshoot. CMAC-ADRC control strategy is a desirable three-motor synchronous control strategy significantly better than the traditional PID control strategy.

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