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Adaptive Compensation Control of Servo System based on LuGre Friction Model

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Abstract

Due to the objective existence of nonlinear and unknown friction, the dynamic and static control performance of me-chanical servo system was seriously affected, gives rise to crawling, oscillation or large steady-state error. In order to realize the high precision control of the servo system, this paper designs a fuzzy logic system which can be adjusted in time according to the control error, to approach the nonlinear and unknown friction of mechanical servo system, based on robust control law of servo system, get system in high precision trajectory tracking control. Simulation results show that the complex friction adaptive control system designed in this paper through the real-time efficient approximation of LuGre model, not only solves the problem that the traditional method of PID control in ultra-low speed control of the flat and crawl of aberration, but also improves the control accuracy of position tracking and velocity tracking.

Keywords

Servo systems; Friction; LuGre model; Fuzzy system; Compensation control.

1. Introduction

In the high accuracy and ultra-low speed servo system, as a result of the existence of nonlinear friction, the dynamic and static performance of the system is greatly affected, which mainly manifested as crawling phenomenon at low speed and greater static error or limit cycle oscillation in steady state [1-3]. Friction is a complex, nonlinear and uncertain natural phenomena. The results of tribology study show that humans' understanding of the physical process of friction is still only in the stages of qualitative one, and it is impossible to apply the mathematical method to accurate description of the friction process [4-6].

For the mechanical servo system, the friction is an obstacle to improve the performance of the system. In order to reduce the negative affect of the friction in the mechanical servo system, people have summed up many effective methods in a lot of practices: change the structural design of the mechanical servo system to reduce the transmission link; choose a better lubricant to reduce the dynamic and static friction difference; use appropriate control compensation methods to compensate for friction [7-10].

Research on friction modeling and dynamic compensation control technology has a history of nearly one hundred years, but due to the limitations of the early control theory and the development level of tribology, the research in this area has been little progress. After entering 1980s, the research in this field has gradually become active. Many advanced friction model and compensation methods have been proposed one after another, many of which have been successfully applied in control design of mechanical servo system [11-15]. But in this kind of literature, the simple coulomb friction plus viscous friction are used as the friction model, and the effect is not ideal.

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It is very important to select a suitable friction model in servo system identification. The LuGre friction model is the most famous one in control research and is widely used in the high precision control system of machinery [16-18]. The LuGre model is a continuous model using a first-order differential equation to characterize friction phenomena such as Coulomb friction, pre-sliding, variable static friction force, Stribeck model, and friction lag. There is a smooth transition between different frictional phenomena, so it has many applications.

In this paper, an adaptive fuzzy system based on the LuGre friction model is designed to approximate the unknown nonlinear complex friction in the mechanical servo system. Based on this, an adaptive robust control algorithm is designed for the high precision trajectory tracking control of the mechanical servo system.

2. Serrvo System and Lugre Friction Model

For a mechanical servo system, its dynamic equation can be described as

$$J\ddot{\theta} = u - F \tag{1}$$

Where J is the moment of inertia, θ is the rotation angle, u is the input torque for control , and F is the friction torque.

The LuGre model is an extension of the Dahl model. At the same time, it adopts the idea of a bristle model. That is, at the microscopic level, the contact surface can be modeled as a large number of elastic bristles with random behavior. Therefore, the LuGre friction model is modeled based on the average deformation of the bristles. If z represents the average deflection of the bristles, then

$$\dot{z} = \dot{\theta} - \frac{\sigma_0 \left|\dot{\theta}\right|}{g(\dot{\theta})} z \tag{2}$$

with

$$g(\dot{\theta}) = F_c + (F_s - F_c)e^{-(\frac{\dot{\theta}}{V_s})} + \alpha\dot{\theta} \tag{3}$$

The friction torque F is given by the following LuGre model

$$F = \sigma_0 z + \sigma_1 \dot{z} + \alpha\dot{\theta} \tag{4}$$

Where in (2) ~ (4), σ_0 and σ_1 are the dynamic friction parameters, and σ_0 is the stiffness of bristles, σ_1 is microcosmic damping coefficient. F_c , F_s , α and V_s are describing static friction system, which F_c is coulomb friction, F_s is static friction, α is viscous friction coefficient and V_s is switching speed.

$g(\dot{\theta})$ represents the Stribeck effect. If $g(\dot{\theta}) = F_c$ and $\sigma_0 = \sigma_1$, then LuGre model can be simplified into a Dahl model. Assuming that the mean deformation of the bristles is in steady-state motion, and $\dot{z} = 0$, then the Stribeck model is obtained. The function of the LuGre model under different conditions is different. The model is a comprehensive one which can describe various system states [19-21].

3. Fuzzy System and its Approximation Properties

Fuzzy systems generally use product inference, singleton fuzzifier, and center average method to solving ambiguity, therefore the output of a fuzzy system is as follows

$$f(x) = \sum_{l=1}^{M} \theta_l \xi_l(x) = \boldsymbol{\theta}^T \boldsymbol{\xi}(x) \tag{5}$$

Where $\boldsymbol{\theta}=(\theta_1,\cdots,\theta_M)^T$, θ_l are an adjustable parameters, $\xi(x)=(\xi_1(x),\cdots\xi_M(x))^T$ and $\xi_l(x)$ is fuzzy basis function which can be defined as

$$\xi_l(x)=\frac{\prod_{i=1}^{n}\mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\prod_{i=1}^{n}\mu_{F_i^l}(x_i)} \tag{6}$$

Where $\mu_{F_i^l}$ is a Gaussian, triangular or other type of membership function, M is the number of fuzzy basis functions, and n is the number of input variables of the fuzzy logic system.

According to the literature, the fuzzy system has the universal approximation property, and its universal approximation theorem is described as follows:

It is assumed that the domain U is a compact set on R^n, and for any real continuous function $g(x)$ defined on U, and any $\varepsilon>0$, there must be a fuzzy system $f(x)$ such as Eq.(5) to make the following formula established

$$\sup|f(x)-g(x)|<\varepsilon \tag{7}$$

That is, the fuzzy system with product inference engine, singleton fuzzifier, and center average defuzzifier is a universal approximator.

The Eq. (7) shows that fuzzy system is a new universal approximator except for multinomial function approximator and neural network. The advantage of fuzzy system compared with other approximators is that it can effectively use the language information. The universal approximation theorem is the theoretical basis of the fuzzy logic system for nonlinear system modeling, and it also explains the reasons for the successful application of the fuzzy system in practice.

4. Control Method based on Friction Compensation

For the mechanical servo system described in Eq. (1), let $x_1=\theta$ and $x_2=\dot{\theta}$, then we can rewrite Eq. (1) into the state equation as follows

$$\begin{aligned}\dot{x}_1&=x_2\\ \dot{x}_2&=-\frac{F}{J}+\frac{u}{J}\end{aligned} \tag{8}$$

Let x_d be a given signal of the servo system, then the tracking error and speed error can be obtained as follows

$$e=x_1-x_d \tag{9}$$

$$\dot{e}=\dot{x}_1-\dot{x}_d=x_2-\dot{x}_d \tag{10}$$

Error function can be defined as

$$s=ce+\dot{e},\quad c>0 \tag{11}$$

then

$$\begin{aligned}\dot{s}&=c\dot{e}+\ddot{e}=c\dot{e}+\dot{x}_2-\ddot{x}_d\\ &=c\dot{e}-\frac{F}{J}+\frac{u}{J}-\ddot{x}_d\end{aligned} \tag{12}$$

Thus, if $s\to 0$, then $e\to 0$ and $\dot{e}\to 0$.

In Eq. (12), is an unknown friction torque, so the control law cannot be directly designed by it. Because the fuzzy system can approximate any nonlinear function with arbitrary precision, this paper will use the adaptive fuzzy system to approach the unknown nonlinear friction

function in real time, and based on this, the adaptive robust control law is designed to realize the high precision trajectory tracking control of the servo system.
Using the fuzzy system shown in Eq. (5), we set its optimal approximation parameters as

$$\boldsymbol{\theta}^* = \arg\min_{\theta\in\Omega}[\sup_{x\in R^2} | \hat{f}(x|\theta) - F |] \quad (13)$$

Where Ω is a sets of θ, then

$$F = \boldsymbol{\theta}^{*T}\xi(x) + \varepsilon \quad (14)$$

Where ε is the optimal approximation error of the fuzzy system.

$$\begin{aligned} & F - \hat{f}(x) \\ & = \boldsymbol{\theta}^{*T}\xi(x) + \varepsilon - \hat{\boldsymbol{\theta}}^T\xi(x) \\ & = -\tilde{\boldsymbol{\theta}}^T\xi(x) + \varepsilon \end{aligned} \quad (15)$$

Where $\tilde{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}} - \boldsymbol{\theta}^*$.
Defining the Lyapunov function as

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{\boldsymbol{\theta}}^T\tilde{\boldsymbol{\theta}} \quad (16)$$

Where $\gamma > 0$, then

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{\gamma}\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}} \\ &= s(c\dot{e} - \frac{F}{J} + \frac{u}{J} - \ddot{x}_d) + \frac{1}{\gamma}\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}} \end{aligned} \quad (17)$$

Design control law as

$$u = J[-c\dot{e} + \frac{\hat{f}(x)}{J} + \ddot{x}_d - \eta\,\mathrm{sgn}(s)] \quad (18)$$

then

$$\begin{aligned} \dot{V} &= s(-\frac{F}{J} + \frac{\hat{f}(x)}{J} - \eta\,\mathrm{sgn}(s)) + \frac{1}{\gamma}\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}} \\ &= s[\frac{1}{J}(\hat{f}(x) - F) - \eta\,\mathrm{sgn}(s)] + \frac{1}{\gamma}\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}} \\ &= s[\frac{1}{J}(\tilde{\boldsymbol{\theta}}^T\boldsymbol{\xi}(x) - \varepsilon) - \eta\,\mathrm{sgn}(s)] + \frac{1}{\gamma}\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}} \\ &= -\frac{1}{J}\varepsilon s - \eta|s| + \tilde{\boldsymbol{\theta}}^T(\frac{1}{\gamma}\dot{\hat{\boldsymbol{\theta}}} + \frac{1}{J}s\boldsymbol{\xi}(x)) \end{aligned} \quad (19)$$

Take $\eta > \frac{1}{J}|\varepsilon|_{\max}$, the adaptive law is designed as

$$\dot{\hat{\boldsymbol{\theta}}} = -\frac{1}{J}\gamma s\xi(x) \quad (20)$$

then $\dot{V} = -\frac{1}{J}\varepsilon s - \eta|s| < 0$. According to Lyapunov stability theorem, the system is stable and all state parameters tend to zero.

5. Simulation Analysis

Consider the servo system shown in Eq. (1) and the LuGre friction model shown in Eq. (2) ~ (4), including $J = 1.0$, $\sigma_0 = 260$, $\sigma_1 = 250$, $F_c = 0.28$, $F_s = 0.34$, $\alpha = 0.02$ and $V_s = 0.01$. Take a sinusoidal signal $x_d(t) = 0.1\sin(t)$ as the servo system input command signal.

The control law based on fuzzy approximation designed in Eq. (18) is adopted, of which $\hat{f}(x)$ are adaptive fuzzy systems, and the input of the fuzzy system has two variables, which are the actual position output and the speed output of the servo system. In order to compare the superiority of the method designed in this paper, compare the method designed in this paper with the commonly used PID control in the project, and compare the control effect of the two methods on the servo system in Eq.(1). In this simulation experiment, system 1 is PID control system, and system 2 is adaptive control system based on friction compensation.

The comparison of control effects between the two control systems is shown in Fig.1 to Fig.4. Fig.1 and Fig.2 are the position tracking and position tracking error comparison; Fig.3 and Fig.4 are the velocity tracking and speed tracking error comparison. From the above simulation results, we can see that the waveform distorts, meanwhile, the position tracking "flat top" phenomenon and the speed tracking "dead zone" phenomenon occur when the velocity is zero using PID control. However, the adaptive control system based on friction compensation in this paper not only does not appear the "flat top" and "dead zone" phenomenon, but the tracking precision is improved greatly.

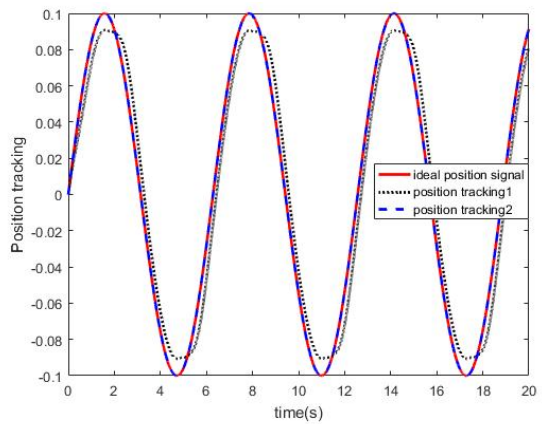

Fig.1. Comparison of position tracking effect

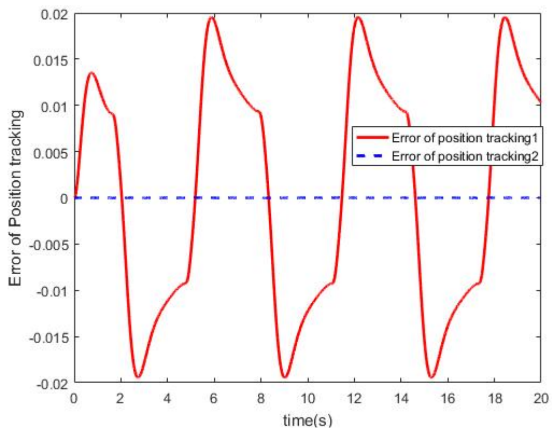

Fig.2. Comparison of position tracking error

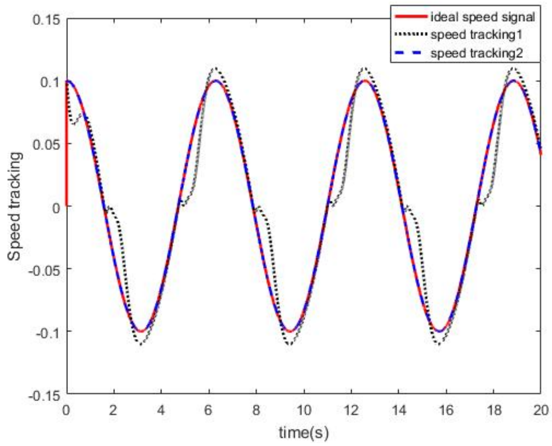

Fig.3. Comparison of speed tracking effect

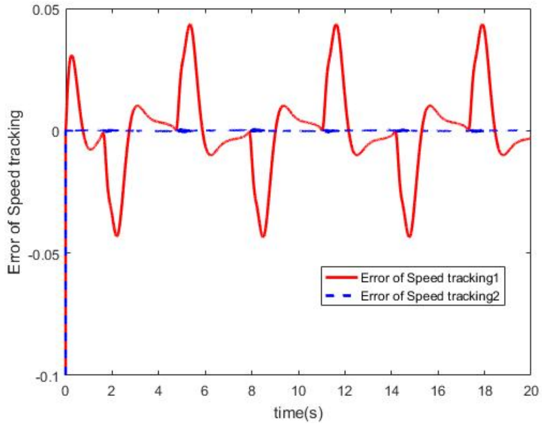

Fig.4. Contrast of velocity tracking error

Fig.5 is the LuGre friction and its real-time compensation effect. It can be seen that the adaptive fuzzy system designed in this paper can achieve real-time compensation for complex friction.

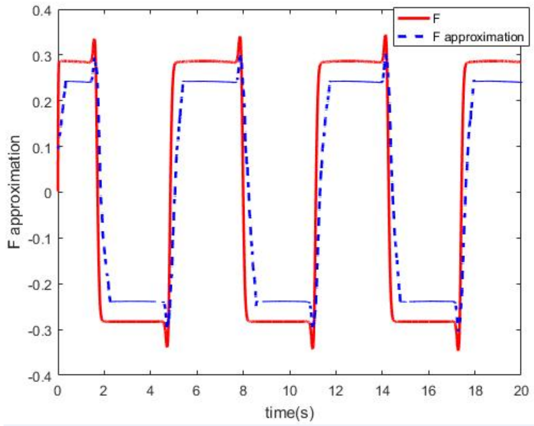

Fig.5. The approximation effect of LuGre friction friction model

The simulation results show that the adaptive control method based on friction compensation can achieve real-time compensation for the complex unknown nonlinear friction, obviously improve the control quality of the servo system and prevent crawling, flat roofing and other undesirable phenomena.

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6. Conclusion

There is an unknown nonlinear friction in the mechanical servo system, which will cause the problem of poor dynamic and static servo control in the traditional control. The fuzzy logic system has the universal approximation property, which can make real-time approximation to the unknown friction of the servo system. In this paper, an adaptive fuzzy approximation system is designed for the LuGre friction model of servo system, and on this basis, the high precision trajectory tracking control of servo system is realized. The simulation results show that the adaptive fuzzy approximation system can well compensate the unknown complex friction in the servo system, and accurately reproduce the complex dynamic and static characteristics of the actual process. The control precision of the control system is improved obviously. The position tracking and speed tracking can meet the requirements of high precision and ultra-low speed control.

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