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Adaptive control of servo system based on LuGre model

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Abstract. This paper established a mechanical model of feed system based on LuGre model. In order to solve the influence of nonlinear factors on the system running stability, a nonlinear single observer is designed to estimate the parameter z in the LuGre model and an adaptive friction compensation controller is designed. Simulink simulation results show that the control method can effectively suppress the adverse effects of friction and external disturbances. The simulation show that the adaptive parameter is between 0.11-0.13, and the value of gamma1 is between 1.9-2.1. Position tracking error reaches level $10^{-3}$ and is stabilized near 0 values within 0.3 seconds, the compensation method has better tracking accuracy and robustness.

1. Introduction
With the progress of science and technology, more and more machining accuracy requirements are put forward for NC machine tools [1-2]. However, due to the nonlinear friction disturbance, the ball screw feed system in the traditional control methods cannot meet the requirements of high precision control[3].

The key of friction compensation is to establish accurate friction model, and calculate the friction force of the system according to the speed, position etc. The friction model can be divided into static and dynamic[4]. At present, the LuGre model is the most widely used, the model accurately describes the dynamic and static characteristics of frictional, and has a good compensation effect. Kamalzadeh[5] proposed for the adaptive sliding mode controller for axial vibration characteristics of ball screw feed system model; Choi J[6] establish dynamic friction model according to LuGre model, show the friction hysteresis characteristic of the system, and apply it to the system sliding mode controller; Zhou Jinzhu[7] has designed a nonlinear observer according to the LuGre model, and the integral backstepping adaptive control algorithm is used.

This paper set up mechanics model of the NC system based on LuGre model, an adaptive friction compensation method is designed, analyses the stability of the adaptive control method and asymptotic convergence, and the validity of the compensation method is verified by simulation.

2. Feed system dynamics modeling
The simplified physical model of the feeding system of NC machine tools is shown in Figure 1:
The equation of motion of the work table:

\[ m \ddot{x} = F_D - F_f - F_r \]  (1)

Where \( m \) - table quality; \( x \) - axial displacement of table; \( F_D \) - driving force of the table; \( F_f \) - friction force of the work table; \( F_r \) - The disturbance force of the worktable.

Equations of motion of the motor screw shaft:

\[ m \ddot{\theta} = J_k u - D \dot{\theta}_m - M_f - T_r \]  (2)

Where \( J_m \) - equivalent rotational inertia of feed system; \( \dot{\theta}_m \) - Motor shaft-screw rotation angle; \( K \) - motor torque constant; \( u \) - control quantity; \( D \) - equivalent damping coefficient of feed system; \( F_{sr} \) - screw load force; \( R \) - lead screw radius.

3. Design of friction compensation controller

Because of the poor robustness of the ordinary PID control, the high-precision tracking requirements cannot be achieved, the Backstepping method has unique advantages in dealing with nonlinear control problems. Therefore, for the above dynamic equations, a robust adaptive friction compensation controller is designed by using the Backstepping design method.

In order to observe the \( z \) values in the LuGre friction model, a nonlinear observer is used in the simplified manner, and the equation is as follows:

\[ \dot{\hat{z}} = \dot{\hat{\theta}} - \frac{\left| \hat{\theta} \right|}{g(\hat{\theta})} \hat{z} + k_1 (\sigma_o \hat{z} + \sigma_i \hat{\theta}) + k_2 \left( \sigma_0 - \sigma_i \right) \frac{\left| \hat{\theta} \right|}{g(\hat{\theta})} \]  (7)

Set \( \hat{z} \) as the error of the state observer:

\[ \hat{z} = \hat{\theta} - \frac{\left| \hat{\theta} \right|}{g(\hat{\theta})} \hat{z} + k_1 (\sigma_o \hat{z} + \sigma_i \hat{\theta}) + k_2 \left( \sigma_0 - \sigma_i \right) \frac{\left| \hat{\theta} \right|}{g(\hat{\theta})} \]  (7)
\[
\ddot{z} = z - z^*, \quad \dot{z} = -\frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} z - k_e e + \sigma_0 - \sigma_1 \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \quad (8)
\]

Define position tracking error signal \( e_1 \), and set \( \dot{\theta}_n \) as expected angular displacement:

\[
e_1 = \theta_e - \theta_n, \quad \dot{e}_1 = \dot{\theta}_e - \dot{\theta}_n \quad (9)
\]

Using Lyapunov function without solving the system state equation is a general method to judge the stability of the system. The Lyapunov function \( V_1 \) is selected in order to obtain the expected value of \( \dot{\theta}_n \) from the output error \( e_1 \):

\[
V_i = \frac{1}{2} e_i^2, \quad \dot{V}_i = e_i \dot{e}_i = e_i (\dot{\theta}_e - \dot{\theta}_n) \quad (10)
\]

Using the Backstepping design method to design the reference speed control signal:

\[
\theta_{id} = \dot{\theta}_e + k_e e_1 + k_x \chi, \quad \chi = \int_0^t e_i dt \quad (11)
\]

Where \( \theta_{id} \) - speed control signals; \( k_i > 0; k_x > 0; \chi \) - integration of position tracking errors.

The error between the reference speed \( \theta_{id} \) and the actual speed \( \dot{\theta}_n \):

\[
e_2 = \theta_{id} - \theta_n = \dot{\theta}_m + k_e e_1 + k_x \chi, \quad \dot{e}_2 = \dot{\theta}_e - \dot{\theta}_m + k_e \dot{e}_1 + k_x e_1 \quad (12)
\]

Then:

\[
\dot{e}_1 = e_2 - k_e e_1 - k_x \chi \quad (13)
\]

The following control laws are designed for the system:

\[
K_u = J \left( \dot{\theta}_e + k_e \dot{\theta}_n + k_x \chi \right) + e_1 + k_e e_2 + \alpha \dot{z} \left( \sigma_0 - \sigma_1 \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \right) + \alpha_\theta k_\theta \dot{\theta}_m + \beta_\theta k_\theta \dot{\theta}_m + T \quad (14)
\]

Where \( k_x \) - a positive real number, \( J \) and \( D \) - parameters of parameter \( J \) and \( D \).

Define the Lyapunov function further:

\[
V_z = V_i + \frac{1}{2} k_e \dot{e}_1^2 + \frac{1}{2} k_e e_2^2 - \alpha \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \dot{z}^2 + D \left( k_e e_2 \dot{\theta}_m - \frac{1}{\gamma_4} \dot{\theta}_m \right) + \beta_\theta \left( k_e e_2 k_\theta \dot{\theta}_m - \frac{1}{\gamma_2} \dot{\theta}_m \right) + \alpha_\theta k_\theta \dot{\theta}_m + \beta_\theta k_\theta \dot{\theta}_m + T \quad (15)
\]

Use \( \alpha z - \alpha z = \alpha \dot{z} + \alpha \dot{z} \): then:

\[
\dot{V}_z = -k_e \dot{e}_1^2 - k_e e_2^2 - \alpha \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \dot{z}^2 - \alpha \dot{\theta}_m \left( \sigma_0 - \sigma_1 \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \right) + k_e e_2 \sigma_0 k_\theta \dot{\theta}_m - \frac{1}{\gamma_4} \dot{\theta}_m + \beta_\theta \left( k_e e_2 k_\theta \dot{\theta}_m - \frac{1}{\gamma_2} \dot{\theta}_m \right) + \alpha_\theta k_\theta \dot{\theta}_m + \beta_\theta k_\theta \dot{\theta}_m + T - \dot{\theta}_m \left( k_e e_2 - \frac{1}{\gamma_3} \dot{\theta}_m \right) \quad (16)
\]

The adaptive law is chosen as:

\[
\dot{\theta}_n = \gamma_\theta k_\theta e_2 \left( \sigma_0 - \sigma_1 \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} + \sigma_0 k_\theta \dot{\theta}_m \right), \quad \dot{\theta}_n = \gamma_\theta k_\theta e_2 \mu_\theta k_\theta \dot{\theta}_m, \quad \dot{\theta}_n = \gamma_\theta k_\theta e_2, \quad \dot{\theta}_n = \gamma_\theta k_\theta e_2 \theta_m \quad (17)
\]

Then:

\[
\dot{V}_z = -k_e \dot{e}_1^2 - k_e e_2^2 - \alpha \frac{k_\theta \dot{\theta}_m}{g(k_\theta \dot{\theta}_m)} \dot{z}^2 \leq 0 \quad (18)
\]

So the equation (14) and (17) can guarantee the system to be globally asymptotically stable.

4. Adaptive friction compensation simulation

In order to verify the effectiveness of the integral backstepping adaptive compensation algorithm, the system is simulated and verified by Matlab/Simulink.
Figure 2. Simulation block diagram of adaptive friction compensation system

LuGre simulation parameters are selected as follows: \( M_s = 340 \text{N}, \ M_c = 280 \text{N} \), \( \mu_b = 0.02 \text{Ns/m} \), \( \sigma_0 = 260 \text{N/m} \), \( \sigma_1 = 2.5 \text{Ns/m} \), \( \theta = 0.01 \text{m/s} \), \( J = 0.2 \text{kgm}^2 \). In simulation, the adaptive parameters are adjusted constantly to achieve good tracking effect. The initial values of the adaptive coefficients are as follows: \( k_c = 80 \), \( k_1 = 13 \), \( k_2 = 1 \), \( k_3 = 0.1 \), \( k_0 = 0.1 \), \( \gamma_1 = 2 \), \( \gamma_2 = 10 \), \( \gamma_3 = 10 \), \( \gamma_4 = 5 \).

Diagram (a) and (b) in Figure 3 is based on the initial values of the above adaptive coefficients. Diagram (a) showing concussion in starting time, to curb this phenomenon need to adjust the parameters.

Figure 3. Speed tracking and position tracking effect

When the value of the adaptive coefficients are: \( k_c = 80 \), \( k_1 = 10 \), \( k_2 = 1 \), \( k_3 = 13 \), \( k_0 = 0.1 \), \( k_z = 0.12 \), \( \gamma_1 = 2 \), \( \gamma_2 = 100 \), \( \gamma_3 = 100 \), \( \gamma_4 = 75 \), the speed tracking effect obtained by simulation are shown as in Figure 3 (b). When the value of \( k_z \) is between 0.11-0.13 and gamma 1 is between 1.9-2.1, the tracking effect is shown in Figure 3 (b). The phenomenon of starting and stopping vibration is obviously eliminated and good tracking result is achieved.

Select sine input signal as figure 4(a) and the simulation time is set to 50s:

Figure 4. System input signal and friction torque and tracking error

Figure 4(b) and (c) shows the friction and position error curves. The position tracking error reaches 10-3, and within 0.3 seconds it is stable near 0 values. There is no large chattering in the whole process, and it has higher tracking accuracy. The friction force varies with the speed of motion, and tends to converge.
5. Conclusion

(1) The friction compensation can control the system motion error within $10^{-3}$ level, and the tracking error is quickly stabilized near 0 values.

(2) The friction compensation method can inhibition the influence of nonlinear factors. By adjusting the adaptive parameters ($k_0$, $k_z$, and $\gamma_i$), the phenomenon of starting and stopping vibration can be avoided effectively. The value of $k_c$ is between 0.11-0.13, and the value of $\gamma_i$ is between 1.9-2.1. The compensation method is insensitive to external disturbances and has strong stability.

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