Sliding Mode Robustness Control Strategy for Shearer Height Adjusting System

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Abstract
This paper firstly established mathematical model of height adjusting hydro cylinder of the shearer, as well as the state space equation of the shearer height adjusting system. Secondly we designed a shearer automatic height adjusting controller adopting the sliding mode robustness control strategy. The height adjusting controller includes the sliding mode surface switching function based on Ackermann formula, as well as sliding mode control function with the improved butterworth filter. Then simulation of the height adjustment controller shows that the sliding mode robustness control solves buffeting of typical controller, and achieves automatic control for the rolling drum of the shearer.

Keywords: shearer, height adjusting, sliding mode, robustness

1. Introduction

The fully mechanized coal face is the most complex working procedure in the coal mine. The shearer is the main equipment on the coal face, whose automation is important in the whole working automation [1]. Furthermore, one of automation of the shearer is the drum height adjusting automation [2], the two drums adjust automatically to get the maximum percentage extraction and avoid cutting the rock, as shown in figure1. However, lots of problems remain to be solved. As a matter of fact, the drum height adjusting is obtained by adjusting the fluid cylinder.
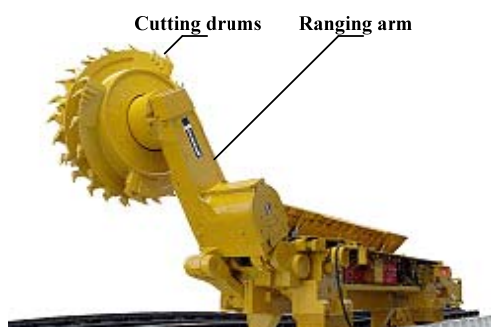

Figure 1. Schematic Diagram of the Shearer

The automatic height adjusting of the shearer aims at fast, steady and precise height adjusting. Some scholars have researched on these. Zhang Junmei et al. [3] researches a shearer height adjusting servo control system, applying a recognition element based on natural γ ray for coal rock identification, γ ray probe detector demands the roof or floor wall rock have someγray radiation,so this method has error and needs improving because of the geological conditions complex. Zhang xiurong et al. [4] has established a proportion closed loop control system, by using the pilot type proportional directional control val as the master element, and a

magnetostrictive displacement sensor as the detecting element, this detecting element can measure position signal of the cylinder rod, this system applied the classical PID control algorithm to adjust the hydraulic liquid flow and achieved fluid cylinder telescopic amount controlling, in this way the position accuracy for the piston was guaranteed, but the dynamic performance needs to improved. Liu chunsheng et al. [5-6] proposed a memory programmable cutting technology and researched switch control characteristics of the solenoid valve controlled hydraulic cylinder combining with fuzzy algorithm and gray association analysis. Wang zhongbin et al. [7] designed a self-adapting height adjusting control system using artificial immunity and memory cutting. Fan qigao et al. [8-10] built a shearer kinematics model of the height adjusting machanism and designed a height adjusting controller by dynamic fuzzy neural network. From the above we can see, researches about robustness of the height adjusting controlling system are not perfect. In this paper, we build a new shearer automatic height adjusting system.

2. Analysis of the Shearer Height Adjusting System

As shown in Figure 2, the shearer height adjusting system includes the cutting drum, the rocker, the height adjusting hydro cylinder and the hydraulic control circuit. In the hydraulic control circuit, two pilot operated check valves constitute a locking circuit so the piston can be locked at any position. Meanwhile, electro hydraulic proportional valve controls the direction and the flow rate of the fluid so that hydraulic cylinder piston reciprocates by rectilinear motion. According to reference [11], we consider the shearer height adjusting load characteristic as mass load, and ignore viscous damping coefficient of the piston motion and external disturbance, transfer function between the displacement of the hydro cylinder and the valve flow rate is:

$$\frac{X_p}{Q_p} = \frac{K_q \dfrac{1}{(2A_1 - A_2)}}{\dfrac{S^3}{\omega_h^2} + \dfrac{2\xi_h}{\omega_h}S^2 + (1 + K_q K_f \dfrac{1}{(2A_1 - A_2)})S} \tag{1}$$

Where:
A_1 and A_2 are effective areas of the two cavities of internal piston in the hydro cylinder;
K_q is the flow rate gain;
K_f is the feedback ratio;
K_p is the equivalent coefficient;
ξ_h is the system damping ratio;
ω_h is the natural frequency.

System state space equation is:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + DU \end{cases} \tag{2}$$

From formula (1), we get:

$$
\begin{cases}
A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_h^2(1 + \dfrac{K_q K_f}{(2A_1 - A_2)}) & -2\omega_h \xi_h \end{bmatrix} \\[6mm]
B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{K_q \omega_h^2}{(2A_1 - A_2)} \end{bmatrix} \\[6mm]
C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \\
D = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}
\end{cases} \tag{3}
$$

Then system state space equation can be calculated as:

$$
\begin{cases}
\dot{X} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_h^2(1+\dfrac{K_qK_f}{(2A_1-A_2)}) & -2\omega_h\xi_h \end{bmatrix} X + \begin{bmatrix} 0 \\ 0 \\ \dfrac{K_q\omega_h^2}{(2A_1-A_2)} \end{bmatrix} U \\
Y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} X
\end{cases}
\tag{4}
$$

Where:
X is the system height adjusting state matrix;
Y is the displacement of the height adjusting hydro cylinder;
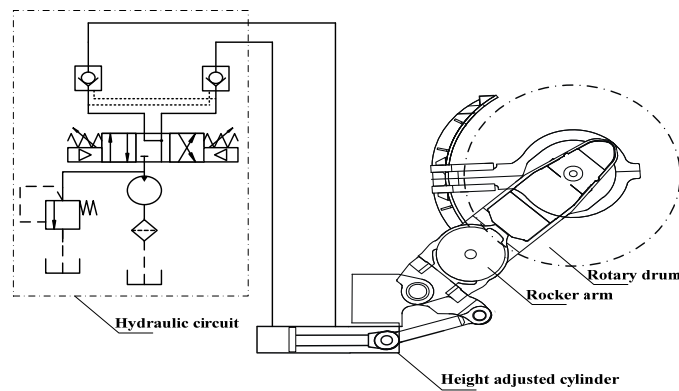U is the input of hydraulic flow rate control;

Figure 2. Schematic Diagram of the Shearer Height Adjusting System

3. Height Adjusting Controller Design of the Shearer

In the shearer cutting procedure, the weight of the rock arm and cutting resistance, as well as the different distribution of the coal quality and the coal seam influence the dynamic response index of the shearer automatic height adjusting system, so we proposed sliding mode robustness control strategy. In this way, efficient trace of the planning cutting route is guaranteed.

Sliding mode robustness control has characteristic of system inflexibility when the system has parameter perturbation and external disturbance [12, 13]. The operational mechanism is: the sliding mode controller switches controlling variables to make the system state slide with the sliding mode surface. As the sliding mode controller requires the system reaches the system state fast and steady and jitter upper and lower, this may cause chattering with high frequency for the shearer height adjusting system [14, 15]. This paper adopts Ackermann formula to design the controller and the sliding mode surface and configures the expectant dynamic pole to improved butterworth filter pole [16, 17]. In this way, the system dynamic response characteristic and robustness are improved, meanwhile the adjustable bipolar sigmoid function instead of switching function and saturation function are used to decrease high frequency buffeting of the output control quantity.

3.1. Switch Surface Design of the Sliding Mode Control

From formula (3) we know A and B in the state equation coefficient matrix are controllable, system deviation of the input and output called system deviation vector is $E = (e_1, e_2, e_3)$, and $e_i = \dot{e}_{i-1}$. From system state equation we get:

$$\dot{E} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_h^2(1 + \dfrac{K_q K_f}{(2A_1 - A_2)}) & -2\omega_h \xi_h \end{bmatrix} E + \begin{bmatrix} 0 \\ 0 \\ -\dfrac{K_q \omega_h^2}{(2A_1 - A_2)} \end{bmatrix} U \qquad (5)$$

As the shearer height adjusting system is controlled by flow rate, which is single input controlling.Given the switching function:

$$s = C^T x \qquad (6)$$

As the system is a three-order system, and $C = (c_1, c_2, 1)$, and $c_3 = 1$. E is the controlled value, then the sliding mode switching function is:

$$s = C^T E = c_1 e_1 + c_2 e_2 + e_3 \qquad (7)$$

The sliding mode is designed. In formula (7), **C** can be calculated by formula Ackermann, s is the switching function. However, sliding mode control law needs to be determined by conditions such as stability of the sliding mode.

3.2. Sliding Mode Control Law Design based on Ackermann
System expected closed-loop pole is obtained by ideal pole distribution of the improved Butterworth filter, and the sliding mode controlling function is designed by Ackermann. The controlling law is:

$$u = u_e + u_d \qquad (8)$$

Where u_e is switching controlling, u_d is equivalent controlling. Then controlling function u_e based on the formula Ackermann is:

$$u_e = -P^T x \qquad (9)$$

Given system state setting value:

$$u = -P^T x + v \qquad (10)$$

As:

$$C^T B = 1 \qquad (11)$$

So:

$$C^T(A - BP^T) = C^T A^* = \lambda_n C^T \qquad (12)$$

As vector C^T is left eigenvector of eigenvector λ_n in matrix A^*. By formula (2), (9) and (12), we get:

$$\dot{X} = A^* x + B[u - u_e] \qquad (13)$$

$s = C_n^T x$ is the state of part n, as state of part n-1 is $z = [x_1, x_2, \ldots, x_{n-1}]$, which is unchangeable, then the n-order system is:

$$\begin{bmatrix} z \\ s \end{bmatrix} = \begin{bmatrix} I & 0 \\ C^T \end{bmatrix} x = Tx \qquad (14)$$

As state transformation array **T** is reversible, by formula (13) and formula (14), the system transformed is:

$$\dot{z} = A_1 z + qs + B_1[u - u_e] \tag{15}$$

$$\dot{s} = \lambda_n s + u - u_e \tag{16}$$

Latent root of **A**$_1$ is combination of conjugate complex number in improved Butterworth filter and real roots λ_i(i=1, 2, …, n), in other words, **A**$_1$ is the ideal dynamic eigenvalue, then:

$$C^{\mathrm{T}}=e^{\mathrm{T}}K(A) \tag{17}$$

$$e^{\mathrm{T}}=(0,…,0,1)(b, Ab, …, A^{n-1}b)^{-1} \tag{18}$$

$$K(\lambda)=(\lambda-\lambda_1)(\lambda-\lambda_2)…(\lambda-\lambda_{n-1}) \tag{19}$$

When $s = C_n^T x$=0, C_n^T is determined by λ_i(i=1, 2, …, n); and when reaching the sliding mode surface, the system trends to ideal dynamic characteristic and is unaffected by λ_n. .Without discontinuous control, u makes the sliding mode is on the hyper plane s=0.
Then:

$$\dot{s} = C^T Ax + u \tag{20}$$

$$u_d=-M(x,t)\mathrm{sign}(s) \tag{21}$$

$$M(x,t)\geq \left| C^{\mathrm{T}}Ax \right| \tag{22}$$

To suppress disturbance, without continuous controlling, the switching function switches the gain and boundary thickness by function Sigmoid. And the function Sigmoid is:

$$\mathrm{sigmoid}(s,\varepsilon)=\frac{1-e^{-\varepsilon s}}{1+e^{-\varepsilon s}} \tag{23}$$

4. System Simulation Analysis

In this part, we firstly determine the system parameter by system transfer function and sliding mode controlling function. Given the hydro cylinder natural frequency 26Hz, subsidence ratio of the hydraulic circuit is ξ_h=0.2.Effective areas of the two cavities of internal piston in the hydro cylinder are calculated by $2A_1$-A_2=15×10^{-3} m^2 . The flow gain is K_q=2 m^2/s,signal feedback ratio is K_q=1.5.We design the sliding mode robustness controller as:

$$u=u_e+u_d=-P^{\mathrm{T}}x-M(x,t)\mathrm{sigmoid}(s) \tag{24}$$

Where $M(x,t)$= CAx+8,pole of controller P is obtained by pole of fourth-order improved Butterworth filter(ω_c=9, φ=π/4),the initial state is X_0=[0.4 0.2 0 0]$^{\mathrm{T}}$.

Given step-function signal and sinusoidalsignal, we simulate the system and trace the step signal by sliding robustness controller.

5. Results and Discussion

As shown in Figure 3 to Figure 8, the system has no oscillation, and trends to reach the balance point gradually, so that the input signal becomes smooth without any buffeting. In the early stage of the step signal tracking process, the time for entering the sliding surface is 3.8s,

and is 0.41s in the early stage of the sine signal tracking process. And both switching function value has remained near 0. Then results show that the stability of system robustness is good.
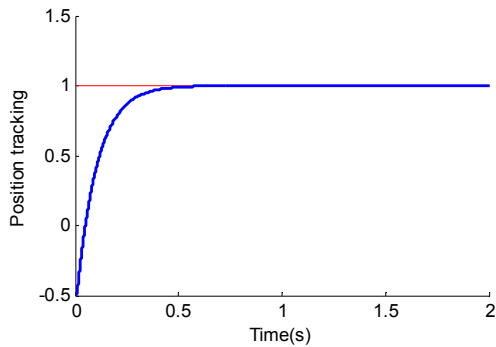
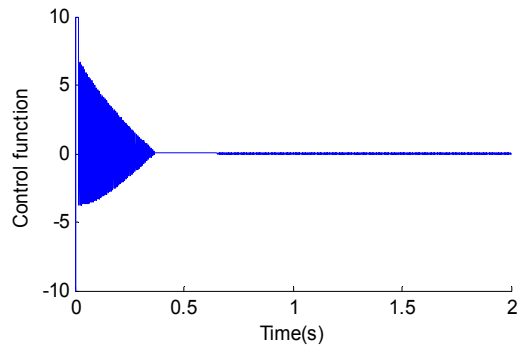Figure 3. Step Signal Tracking Figure of the Sliding Mode Robustness Controlling System

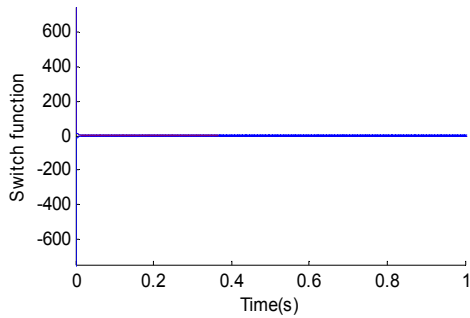Figure 4. Figure of Tracking Controlling Function of Step Signal

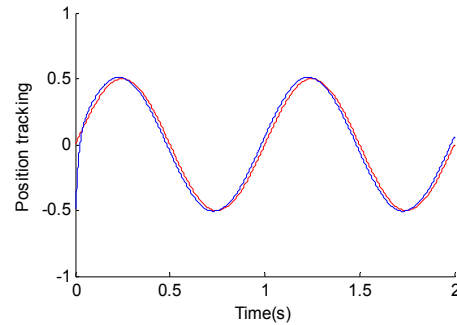Figure 5. Switch Function of Step Signal

Figure 6. Sinusoidal Signal Tracking Figure of the Sliding Mode Robustness Controlling System
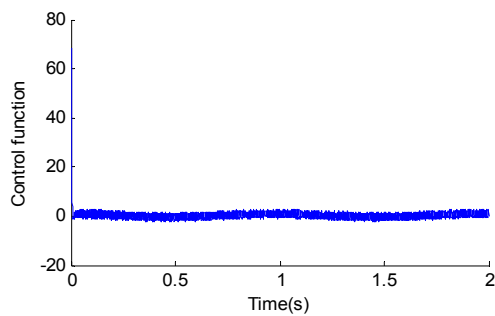
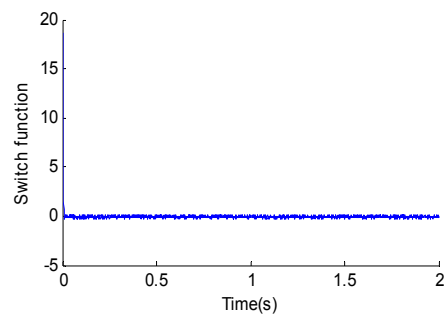Figure 7. Figure of Tracking Controlling Function of Sinusoidal Signal

Figure 8. Switch Function of Sinusoidal Signal

6. Conclusion

(1) The shearer automatic height adjusting is achieved by the sliding mode robustness controlling, the dominant mechanism is: 1) transfer function design of hydro cylinder in the electro-hydraulic servo system and the corresponding system state equation establishment, 2) sliding mode controller switching function s design by system state equation. Then combining

formula Ackermann and improved Butterworth filter, the sliding mode controlling law is designed to get the sliding mode controlling function u of shearer height adjusting system;

(2) Given the initial state of the shearer height adjusting system, we simulate the step signal and the sinusoidal signal by sliding mode robustness controller. Results show that the controller can track the input signal fast and smoothly, which overcomes high frequency buffeting of the typical sliding mode when reaching the sliding mode surface controller.

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