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RESEARCH ON FORCE CONTROL SYSTEM OF LEAD CATHODE LEVELER

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The flatness of the lead cathode plate affects the electrolytic efficiency of lead and the production efficiency of the whole lead electrolytic industry. However, the dynamic response of the force control system of the leveler is slow, and the anti-interference and robustness are poor. By comparing proportion integration differentiation (PID) control and feedback linearized synovial control two control strategies, MATLAB software was used for modeling and simulation analysis. The results show that the system with feedback linearized sliding mode control has faster response, higher precision and better robustness.

Keywords: lead, cathode sheet, levelling machine, force control, sliding mode control algorithm

INTRODUCTION

Non-ferrous lead electrolysis industry has brought great promotion to the development of economy. In the process of industrial production of electric lead, crude lead and fine lead are cast into a certain shape of anode plate and cathode plate respectively. The process diagram of lead electrolysis is shown in Figure 1.

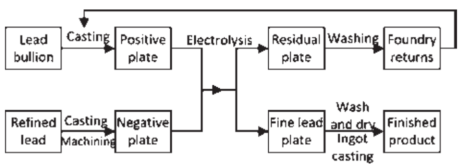

Figure 1 Schematic diagram of lead electrolysis production process

Lead cathode sheet is the lead sheet made by the lead cathode preparation unit after the electrolysis of crude lead, with high purity but uneven thickness and folds. The flatness of lead cathode sheet will affect the electrolytic efficiency of lead, so it is necessary to improve the flatness of lead sheet by leveling and pressing machine, as shown in Figure 2, so as to make the thickness of lead sheet even and the surface smooth, so as to improve the quality and electrolytic efficiency of lead sheet.

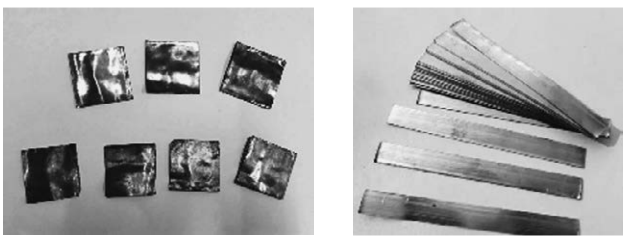

Figure 2 Lead sheet diagram

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LEVELING MACHINE HYDRAULIC CONTROL SYSTEM

The leveling machine needs to squeeze the lead sheet, so the valve control cylinder system is required to adjust the liquid pressure. The hydraulic cylinder of the cathode leveling machine pushes the pressure plate in a cyclic process, which consists of a series of slopes and holding cycles. The working process is shown in Figure 3. In the process of closing the die, the hydraulic oil pushes the hydraulic cylinder out, the convex die pressing plate and the concave die pressing plate move forward, the opening die retracted after closing the die, the punch and the concave die retracted back to the designated position under the push of the piston bit of the hydraulic cylinder[1].

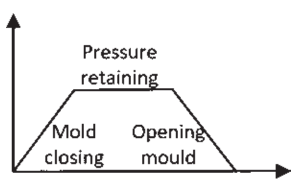

Figure 3 Work process of leveler

In the process of pressure preservation, the force on the lead sheet is maximum, and at this time, the grain is printed on the lead sheet to increase the stiffness of the lead sheet. The principle of a typical valve-controlled asymmetric cylinder system is shown in Figure 4.

In the Figure, X_p represents the displacement of the piston rod, m represents the equivalent load mass, B

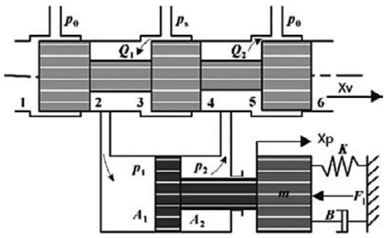

Figure 4 Operating principle of valve controlled cylinder

represents the equivalent load damping, K represents the equivalent load stiffness, F represents the equivalent external load force, X_v represents the spool displacement, A_1 and A_2 respectively represent the effective area of the rodless and roded cavities of the hydraulic cylinder, p_1 and p_2 respectively represent the pressure of the two cavities of the hydraulic cylinder. q_1 and q_2 respectively represent the flow into and out of the two chambers of the hydraulic cylinder.

The three equations are as follows:

1) Servo valve inlet and outlet oil flow

$$q_1 = K_d x_v \sqrt{\left\{ \begin{array}{l} [\dfrac{(1+\operatorname{sgn}(x_v))p_s}{2} + \dfrac{(-1+\operatorname{sgn}(x_v))p_0}{2}] \\ -\operatorname{sgn}(x_v)p_1 \end{array} \right\}}$$

$$q_2 = K_d x_v \sqrt{\left\{ \begin{array}{l} [\dfrac{(1-\operatorname{sgn}(x_v))p_s}{2} + \dfrac{(-1-\operatorname{sgn}(x_v))p_0}{2}] \\ +\operatorname{sgn}(x_v)p_2 \end{array} \right\}} \quad (1)$$

Where $K_d = C_d w\sqrt{2/\rho}$ (K_d is the conversion factor), p_s is the system operating pressure, p_1 is the servo cylinder inlet chamber pressure, p_2 is the servo cylinder return chamber pressure, and p_0 is the system return pressure.

2) Hydraulic cylinder flow continuity equation

$$q_1 = A_1\dot{x}_p + C_{ip}(p_1 - p_2) + C_{ep}p_1 + \frac{V_{g1} + A_1L_0 + A_1x_p}{\beta_e}\dot{p}_1 \quad (2)$$

$$q_2 = A_2\dot{x}_p + C_{ip}(p_1 - p_2) - C_{ep}p_2 - \frac{V_{g2} + A_2(L - L_0) - A_2x_p}{\beta_e}\dot{p}_2 \quad (3)$$

Where C_{ip} is the internal leakage coefficient, C_{ep} is the external leakage coefficient, L is the total stroke of the servo cylinder, L_0 is the initial position of the servo cylinder piston, $A_1$is the area of the rodless chamber of the servo cylinder, A_2 is the area of the rodged chamber of the servo cylinder, x_p is the displacement of the servo cylinder, β_e is the effective volume elastic modulus of the hydraulic oil, V_{a1} is the volume of the piping connecting the servo valve and the servo cylinder inlet, V_{a2} is the volume of the piping connecting the servo valve and the servo cylinder return.

3) Hydraulic cylinder and load balance equation

$$A_1p_1 - A_2p_2 = m\ddot{x}_p + B\dot{x}_p + Kx_p + F + F_f \quad (4)$$

In addition, the electro-hydraulic servo valve is a double nozzle flapper force feedback electro-hydraulic servo valve, and its dynamic model can be described by the proportional link as follows:

$$x_v = K_x K_{axv} x_r \quad (5)$$

Where, K_{axv} is the servo valve gain, x_r is the expected displacement, and K_x is the displacement sensor gain [2,3].

LEVELING MACHINE FORCE CONTROL STRATEGY

The state vector of the system is selected as piston rod displacement x_p, piston rod speed $\dot{x}_p$, pressure without rod cavity p_1 and pressure with rod cavity p_2, then the state vector can be written as

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} x_p & \dot{x}_p & p_1 & p_2 \end{bmatrix}^T \quad (6)$$

The input vector u is $u = x_r$.

According to the definition of relative order, the relative order of the system is obtained as (3). Since the order (4) of the system is greater than its relative order (3), the system has internal dynamic subsystem. According to the feedback linearization method, the transformation relationship between the new state variable and the original state variable is constructed as

$$\begin{cases} z_1 = h(x) = x_1 \\ z_2 = L_f h(x) = x_2 \\ z_3 = L^2{}_f h(x) = -\dfrac{K}{m}x_1 - \dfrac{B}{m}x_2 + \dfrac{A_1}{m}x_3 - \dfrac{A_2}{m}x_4 \end{cases} \quad (7)$$

Then the original nonlinear system equation of state can be transformed into the equation of state in linear space

$$\begin{cases} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v \\ y = z_1 \end{cases} \quad (8)$$

The control quantity u of the nonlinear system under the original coordinates can be obtained by the inverse coordinate transformation of the control quantity v of the linear system.

$$u = (v - \alpha(x)) / \beta(x) \quad (9)$$

When feedback linearization is completed, the order of equation of state (8) of the linear system is (3), which is less than the order of the original system (4), so there is a nonlinear internal dynamic subsystem. In order to achieve accurate stability control of the original system, the internal dynamic subsystem is also required to be stable, that is, the following conditions must be met

$$\frac{\partial \eta}{\partial x}g(x) = \frac{\partial \eta}{\partial x_3}g_1 + \frac{\partial \eta}{\partial x_4}g_2 = 0 \quad (10)$$

Then $\eta = g_1 + g_2$, the dynamic subsystem is stable [4,5].

The system model obtained after feedback linearization is a third-order linear system, so the sliding mode surface can be designed as

$$s = c_1 e + c_2 \dot{e} + \ddot{e} \tag{11}$$

Where c_1, c_2 is the constant of the sliding mode surface.

First determine the equivalent control:

$$\begin{aligned} \dot{s} &= c_1 \dot{e} + c_2 \ddot{e} + e^{(3)} \\ &= c_1(\dot{z}_d - \dot{z}_1) + c_2(\ddot{z}_d - \ddot{z}_1) + (\dddot{z}_d - \dddot{z}_1) \\ &= c_1(\dot{z}_d - \dot{z}_1) + c_2(\ddot{z}_d - \ddot{z}_1) + \dddot{z}_d - v_{eq} \end{aligned} \tag{12}$$

In order to ensure the generation of sliding mode, $s\dot{s} < 0$ is required, so the switching control quantity is selected

$$v_{si} = -k\,\mathrm{sgn}(s) \tag{13}$$

Where, k is the switch control gain.The output of sliding mode control can be expressed as follows:

$$v = c_1 \dot{e} + c_2 \ddot{e} + z_d^{(3)} - k\,\mathrm{sgn}(s) \tag{14}$$

Stability proof: Definition *Lyapunov* function $V = \frac{1}{2} s^2$,

For the third-order linear system after feedback linearization in this paper, there are:

$$s = c_1 e + c_2 \dot{e} + \ddot{e}$$

$$\begin{aligned} \dot{V} &= s\dot{s} = s(c_1 \dot{e} + c_2 \ddot{e} + e^{(3)}) \\ &= s(c_1 \dot{e} + c_2 \ddot{e} + z_d^{(3)} - z_1^{(3)}) \\ &= s(-k\,\mathrm{sgn}(s)) = -k|s| \le 0 \end{aligned} \tag{15}$$

Then the sliding mode control system in the new coordinate system is stable. Since the existence of sign function will cause system flutter, boundary layer function is used instead of sign function to reduce system flutter.

$$sat\left(\frac{s}{\Phi}\right) = \begin{cases} \mathrm{sgn}(s/\Phi) & (|s/\Phi| \ge 1) \\ s/\Phi & (|s/\Phi| < 1) \end{cases} \tag{16}$$

Where, Φ is the boundary layer thickness.

The improved feedback linearized sliding mode control rate can be obtained[6]:

$$u = \frac{c_1 \dot{e} + c_2 \ddot{e} + z_d^{(3)} - k\,sat\left(\frac{s}{\Phi}\right) - L^3{}_f h(x)}{L_g L^2{}_f h(x)} \tag{17}$$

SIMULATION EXPERIMENT AND ANALYSIS

The traditional PID control algorithm and feedback linearized sliding mode control algorithm were modeled on the MATLAB-Simulink platform, as shown in Figure5,6.

The input is a sinusoidal force with a amplitude of 2 000 N and a step force with 5 000 N. The simulation parameters of the linearized sliding mode controller are k = –25 000, $\varnothing$ = 10, and the PID control has the simulation parameters of k_p = 8 000, k_i = 0, k_d = 20. The force tracking curves obtained by using different control algorithms are shown in Figure 7,8.

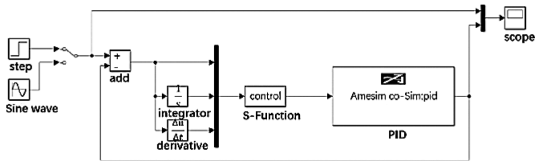

Figure 5 PID control model

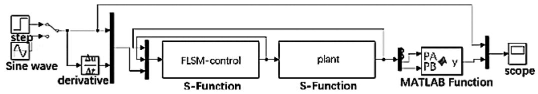

Figure 6 FLSM control model

It can be seen from Figure 7,8 that the feedback linearized sliding mode control algorithm can effectively shorten the adjustment time of the system and the tracking effect of the feedback linearized sliding mode control algorithm is better than that of PID control. This algorithm not only improves the response speed of the system, but also improves the tracking effect of the system.

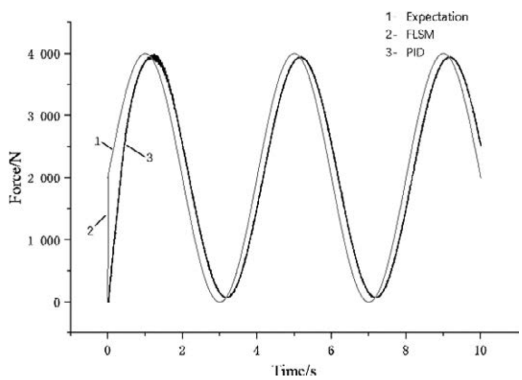

Figure 7 Sinusoidal signal

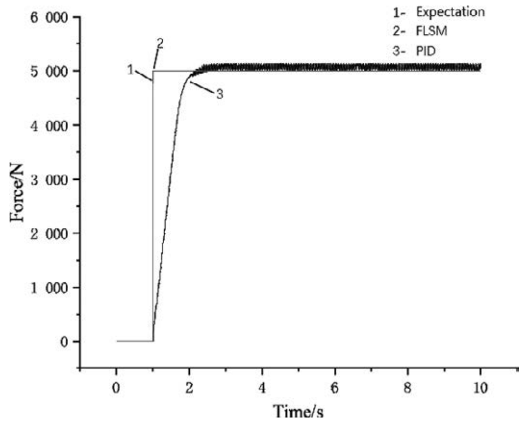

Figure 8 Step signal

CONCLUSION

In this paper, the structure of lead cathode leveling electro-hydraulic servo system is analyzed, and a feedback linearized sliding mode control method is designed and applied to the research of force control of valve cylinder. Through Simulink platform modeling, compared with the simulation experiment, we can see that the feedback linearized sliding mode controller designed in the respectively tracking sine and step force, the overshoot is small and can reach a stable state quickly, the tracking force control process is relatively stable, no chatter, is beneficial to improve the quality of the lead cathode leveler. It has important practical significance to promote the development and progress of nonferrous metal lead electrolysis industry.

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Note: The responsible translator for English language is T.X. Zhang -Hebei Normal University, China.