

Modeling and Sliding Mode Control for Cement Particle Size

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Abstract. Considering the characteristics of large time delay and vulnerable to interference of cement particle size control. Firstly, through the rise curve of the production process to identify the transfer function with time delay by least squares algorithm. Secondly, translate the time delay system into a form of state space equation with no delay by a method of state transition. Finally, an equivalent sliding mode control is applied to control the particle size and the stability conditions of sliding mode control are given. The simulation results show it can achieve a desirable control effect in cement particle size control.

1. Introduction

The control of cement grinding is an essential part in the process of cement production. Reasonable particle size distribution is one of the most concerned for cement grinding process which affects the coagulation rate, hardening process, fluidity and the strength of cement particles^[1] for it directly determines the quality of cement production and economic benefits. Considering the characteristic of the time delay for the control variables change response slowly to the controlled variable, it is difficult to establish an accurate particle size control model. Furthermore, it is of great to research the anti-interference of the grinding control system for the measurement of some variable is vulnerable to noise restricted by the production condition.

There are not much research on the modeling and control of cement particle size in recent years. For example, the paper [2] identify the parameters of the grinding model by regression analysis on base of the structure of the model was ascertained and had not add the delay component. In the paper [3], fuzzy control theory is used to build the cement particle size model, but the formulation of fuzzy rules requires higher experience due to the different grinding process of every cement plant. Document [4] establishes the combined grinding model by ELM neural network in which the selection of hidden layer number and learning rate is hard to make decision and the model established by the neural network is difficult to use in the design of the controller. The adaptive PID controller is designed to control the particle size of cement through the model free adaptive control (MFAC) without considering the disturbance of noise and time delay in article [5]. The sliding mode control based on exponential approach law is used to control the mill load without thinking about the problem of delay in article [6]. In summary, the time delay problem had not being taken into account the above research about modeling and control of cement particle size.

The identification of the transfer function model through the flying curve [7] is a popular method in industrial control. In this paper, through the analysis of the production data to determine the structure model of the particle size control system and then identify the unknown parameters of model based on least square algorithm. The basic ideal of sliding mode variable structure control is to lead the target state move in a predetermined sliding mode according to the current state of the system which makes the



corresponding parameter disturbances insensitive for the design of sliding mode is independent of object parameters and perturbations[8]. The insensitivity to disturbance and noise of sliding mode control is the main reason for the application in cement particle size control.

2. The grinding process of cement clinker

A cement grinding process is briefly described as follows and the technological process shows in Fig. 1.

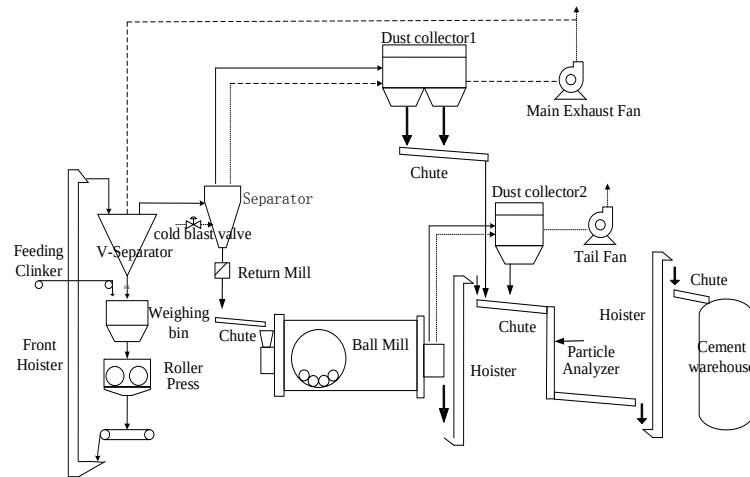


Figure 1. The cement grinding process

(1) Clinker, limestone, fly ash, slag, gypsum and other materials get into weighing bin in a certain proportion and then the mixed material entering roller press staley.

(2) After the primary grinding of the roller press, the material enters the V-separator to scatter and classify and then the coarse material enters the weighing bin again, the fine material enters the separator.

(3) Through the screening of the separator, the finer part get into the dust collector 1 under the effect of the main exhaust fan, at the same time, the thicker part enters the ball mill.

(4) After the grinding process of ball mill, the finer part get into the dust collector 2 under the drive of the tail fan, and other materials go into the cement warehouse.

In order to keep the controllability and quite stability of the cement grinding system, fewer variables are allowed to be adjusted in actual control process. Based on the above clinker grinding process and take the proportion of particle size less than $3\mu\text{m}$ as the control target, adjust the speed of the tail fan in a certain range can keep the granularity of less than $3\mu\text{m}$ stable when the mill load is normal. Similarly, control the size proportion of the $3-32\mu\text{m}$ only need to adjust the speed of the separator. Only when the tail fan and the separator has reached an adjustable range need to regulate the speed of main exhaust fan.

Combined the actual production commissioning process with the experience of advanced operators; we can calculate a routine adjustment range show as the follow table 1.

Table 1. A group of ideal control ranges

Particle size	Scope of size	Main regulate factor	Scope of speed
$<3\mu\text{m}$	11.5-13.5%	Speed of tail fan	550-850rpm
$3-32\mu\text{m}$	55-60%	Speed of separator	1250-1400rpm

In this paper, the relationship between the $3-32\mu\text{m}$ particle size and the speed of the separator is taken as an example to study the modeling and control.

3. The cement particle size model based on least square algorithm

From the above process analysis we can know that when the speed of the separator is changed, the corresponding particle size of the cement must be grinded through the ball mill first and then be

collected by the particle analyzer. It requires a longer process which reflects a larger control delay characteristic.

In order to demonstrate the delay process, we give a higher speed of separator in the condition of the cement is quite stability and the 3-32 μ m particle size curve is given as follows.

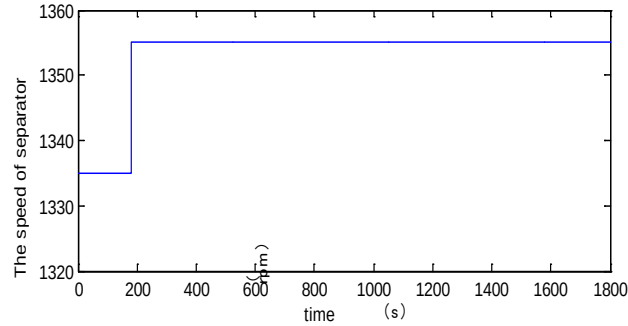


Figure 2. The variation of the control signal

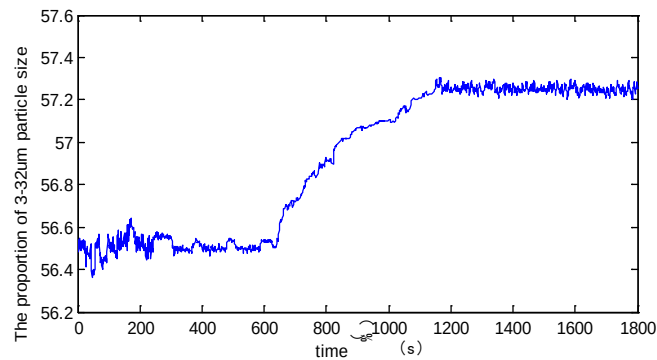


Figure 3. The variation of controlled variable

It is obvious that the particle size of cement will be delayed for a period of time to response after a change of the speed of the separator and the response process curve of particle size approximate a flying curve. The commonly used industrial time-delay systems can be assumed to be a transfer function composed of inertial link and time-delay link^[9]. Considering the following transfer function as a particle size model

$$G(s) = \frac{Ke^{-\tau s}}{(T_1s+1)(T_2s+1)} \quad (1)$$

Where, K is the gain coefficient, τ is the delay time, T_1 and T_2 are the inertia coefficient. Set the sampling period as T_s , discrete the formula (1) by zero-order holder, where $G(z) = (1-z^{-1})Z[\frac{G(s)}{s}]$, set $d = \tau / T_s$

$$\text{We can get } G(z) = \frac{Y(z)}{U(z)} = \frac{b_1z^{-1} + b_2z^{-2}}{1 - a_1z^{-1} - a_2z^{-2}} \cdot z^{-d}$$

Where

$$\left\{ \begin{array}{l} a_1 = (e^{-\frac{T_s}{T_1}} + e^{-\frac{T_s}{T_2}}) \\ a_2 = -e^{-\frac{T_s}{T_1} + \frac{T_s}{T_2}} \\ b_1 = K \cdot [\frac{T_1 e^{-\frac{T_s}{T_1}} - (T_2 - 2T_1) e^{-\frac{T_s}{T_2}}}{T_2 - T_1} + 1] \\ b_2 = K \cdot [e^{-\frac{T_s}{T_1} + \frac{T_s}{T_2}} + \frac{T_1 e^{-\frac{T_s}{T_2}} - T_2 e^{-\frac{T_s}{T_1}}}{T_2 - T_1}] \end{array} \right. \quad (2)$$

The difference equation of (1) is written as

$$y(k) = a_1 y(k-1) + a_2 y(k-2) + b_1 u(k-d-1) + b_2 u(k-d-2) \quad (3)$$

Taking the sampling period $T_s = 1s$. From Fig.1 and Fig.2 we can know that the delay coefficient τ is in a certain interval, we roughly select $\tau \in [300, 600]$. so $d = \tau / T_s \in [300, 600]$. To determine the value of d , the equation under different delay d can be written as

$$\hat{y}_d(k) = a_1 y(k-1) + a_2 y(k-2) + b_1 u(k-d-1) + b_2 u(k-d-2) \quad (4)$$

Taking the mean square error (MSE) to evaluate the model

$$MSE(d) = \frac{1}{n} \sum_{k=1}^n [y(k) - \hat{y}_d(k)]^2 \quad (5)$$

Parameters need to be identified is $\theta = [a_1, a_2, b_1, b_2]^T$ and consider the constraint condition of formula (2) to identify parameters by the least squares algorithm^[10].

$$\hat{\theta} = (\Phi^T \Phi)^{-1} \Phi^T Y \quad (6)$$

Where

$$\Phi = \begin{bmatrix} y(n-1) & y(n-2) & u(n-d-1) & u(n-d-2) \\ y(n) & y(n-1) & u(n-d) & u(n-d-1) \\ \vdots & \vdots & \vdots & \vdots \\ y(n+N-1) & y(n+N-2) & u(n+N-d-1) & u(n+N-d-2) \end{bmatrix}$$

$$Y = [y(n) \quad y(n+1) \quad \cdots \quad y(n+N)]^T$$

Where, n is the initial sequence of data, N is the length of training data.

The mean square error in different d estimate by least squares is shown in the follow Fig.4.

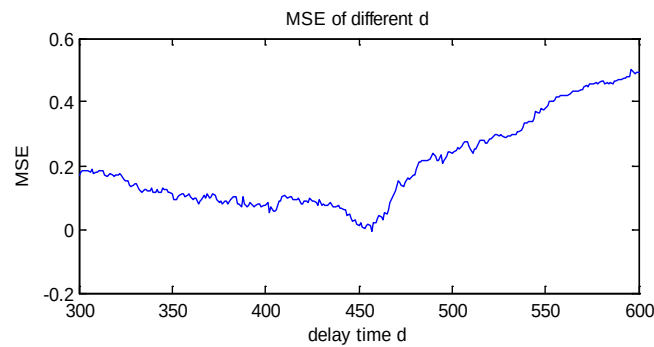


Figure 4. Least mean square error under different time delay

The optimal delay coefficient in the case of minimum mean square error is $d = 457$. Calculating the least square estimation parameters under the optimal delay d and the particle size fitting curve and the error curve are shown in the following Fig.5 and Fig.6.

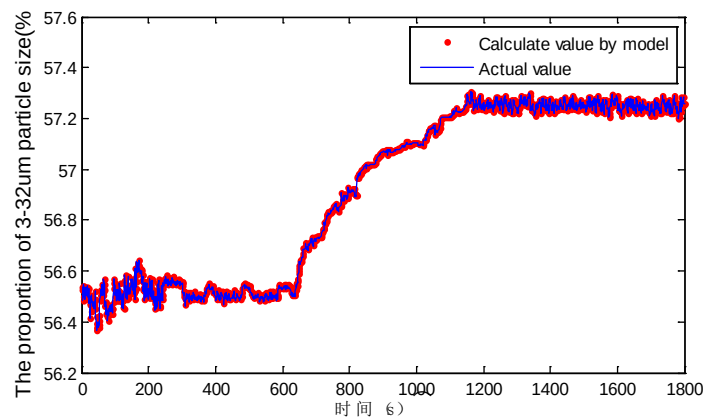


Figure 5. The least square fitting curve under the best time delay

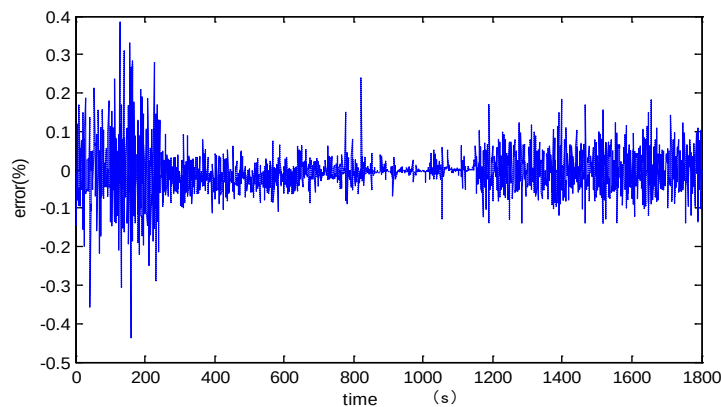


Figure 6. The fitting error curve

We can get the identification parameters $a_1 = 1.1879$, $a_2 = -0.1902$, $b_1 = 0.026$, $b_2 = 0.0002$. Through the relational expression (2) work out $T_1 = 1.39$, $T_2 = 792.84$, $K = 0.026$. Then the transfer function is expressed as follows.

$$G(s) = \frac{0.026e^{-457s}}{(1.39s + 1)(792.84s + 1)} \quad (7)$$

4. Sliding mode control for the cement particle size

The fundamental idea of sliding mode control is to change the structure according to the target state to approximate the pre designed sliding surface^[11] which can be designed irrelevant to the external disturbance, noise and other uncertain factors^[12]. This determines the strong anti-interference performance of the sliding mode system and makes it particularly suitable for industrial control processes.

Considering the system state space equation with control time delay:

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}u(k-d) \quad (8)$$

Where, d is the control delay and $d \geq 1$. In order to transform the equation (8) into an expression without delay, references the article [14], we take a new state vector $\bar{\mathbf{x}}(k)$

$$\bar{\mathbf{x}}(k) = \mathbf{A}^d \mathbf{x}(k) + \sum_{m=0}^{d-1} \mathbf{A}^m \mathbf{B}u(k-m-1) \quad (9)$$

We can get the expression without delay

$$\bar{\mathbf{x}}(k+1) = \mathbf{A}\bar{\mathbf{x}}(k) + \mathbf{B}u(k) \quad (10)$$

Translate the equation (10) into an error state space equation. Suppose the tracking signal is $\mathbf{R}(k)$, the error state vector is

$$\mathbf{x}_e(k) = \mathbf{R}(k) - \bar{\mathbf{x}}(k) \quad (11)$$

Bring the equation (11) into the equation (10) get

$$\mathbf{x}_e(k+1) = \mathbf{A}_e \mathbf{x}_e(k) + \mathbf{B}_e u(k) + \mathbf{f}(k) \quad (12)$$

Where, $\mathbf{A}_e = \mathbf{A}$, $\mathbf{B}_e = -\mathbf{B}$, $\mathbf{f}(k) = -\mathbf{A}\mathbf{R}(k) + \mathbf{R}(k+1)$.

The switching function is designed to

$$s_e(k) = \mathbf{C}_e \mathbf{x}_e(k) \quad (13)$$

When the discrete system enters the quasi sliding mode, it satisfy $s_e(k) = s_e(k+1)$, so there is

$$\mathbf{C}_e \mathbf{x}_e(k) = \mathbf{C}_e [\mathbf{A}_e \mathbf{x}_e(k) + \mathbf{B}_e u(k) + \mathbf{f}(k)] \quad (14)$$

We can get the equivalent control law

$$u_{eq}(k) = -(\mathbf{C}_e \mathbf{B}_e)^{-1} [\mathbf{C}_e (\mathbf{A}_e - \mathbf{I}) \mathbf{x}_e(k) + \mathbf{C}_e \mathbf{f}(k)] \quad (15)$$

The total control law is designed as

$$u(k) = u_{eq}(k) + \mathbf{F}_D \mathbf{x}_e(k) \quad (16)$$

Where, the gain of the system state variable is

$$\mathbf{F}_D = [f_1, f_2, \dots, f_n] \quad (17)$$

Delimiting

$$\delta_i = \frac{1}{2} f_0 (\mathbf{C}_e \mathbf{B}_e)^2 |x_{ei}(k)| \sum_{i=1}^n |x_{ei}(k)|$$

$$f_i = \begin{cases} f_0 & \mathbf{C}_e \mathbf{B}_e s_e(k) x_{ei}(k) < -\delta_i \\ 0 & -\delta_i \leq \mathbf{C}_e \mathbf{B}_e s_e(k) x_{ei}(k) \leq \delta_i \\ -f_0 & \mathbf{C}_e \mathbf{B}_e s_e(k) x_{ei}(k) > \delta_i \end{cases} \quad (18)$$

We can know the conditions of f_0 can be determined in article [11].

$$0 < f_0 < \frac{2 |s_e(k)|}{|\mathbf{C}_e \mathbf{B}_e| \sum_{i=1}^n |x_{ei}(k)|} \quad (19)$$

To sum up, in the conditions of (18) and (19) the control law (16) of the equivalent sliding mode control of discrete systems with control time delay can achieve a stable effect.

5. Simulation

The transfer function (7) of the cement system can be transformed into discrete state space equations as follows.

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k) + \mathbf{B}u(k-d) \\ y(k) &= \mathbf{C}\mathbf{x}(k) + D \end{aligned} \quad (20)$$

Where, $\mathbf{A} = \begin{bmatrix} 0 & 1 \\ -0.000907 & -0.72 \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} 0 \\ 0.0000236 \end{bmatrix}$, $\mathbf{C} = [1, 0]$, $D = 0$.

Taking a new state variable $\bar{\mathbf{x}}(k)$ to translate the equation (20) into a state space equation without time delay:

$$\bar{\mathbf{x}}(k) = \mathbf{A}^d \mathbf{x}(k) + \sum_{m=0}^{d-1} \mathbf{A}^m \mathbf{B}u(k-m-1) \quad (21)$$

$$\bar{\mathbf{x}}(k+1) = \mathbf{A}\bar{\mathbf{x}}(k) + \mathbf{B}u(k) \quad (22)$$

Translating the equation (22) into an error state space equation:

$$\mathbf{x}_e(k+1) = \mathbf{A}_e \mathbf{x}_e(k) + \mathbf{B}_e u(k) + \mathbf{f}(k) \quad (23)$$

Where, $\mathbf{A}_e = \mathbf{A}$, $\mathbf{B}_e = -\mathbf{B}$, $\mathbf{f}(k) = -\mathbf{A}\mathbf{R}(k) + \mathbf{R}(k+1)$.

The target value of the controlled object take as $r(k)$ and its rate of change as $dr(k)$. So in the formula (23) we have $\mathbf{R}(k) = [r(k), dr(k)]^T$ and $\mathbf{R}(k+1) = [r(k+1), dr(k+1)]^T$. Using linear extrapolation method [15] to predict $r(k+1)$ and $dr(k+1)$.

$$\begin{aligned} r(k+1) &= 2r(k) - r(k-1) \\ dr(k+1) &= 2dr(k) - dr(k-1) \end{aligned} \quad (24)$$

The initial value of the particle size of the cement is $r(0) = 56\%$ and the target value is $r(k) = 57\%$, using the form of control law (15)~(17), set $\mathbf{C}_e = [50, 1]$ and select the sampling period $T_s = 1s$, giving a step interference signal with a value of 0.1 in the time of 2000s, under the constraint condition of inequality (19) take

$$f_0 = \frac{0.1 |s_e(k)|}{|C_e B_e| \sum_{i=1}^n |x_{ei}(k)|} \quad (25)$$

The simulation result is shown in figure 7 to figure 9.

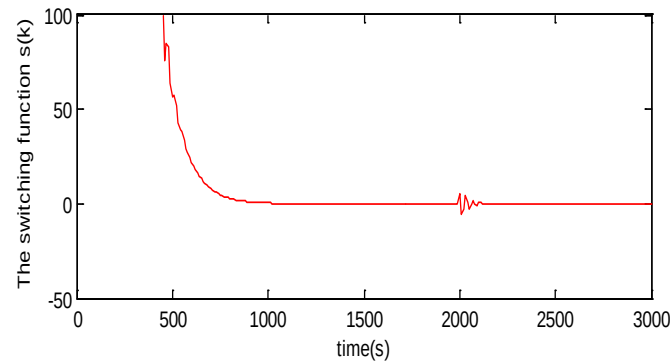


Figure 7. The switching function

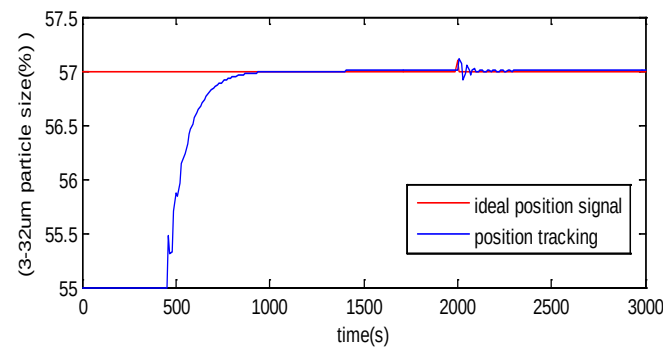


Figure 8. Particle size tracking curve

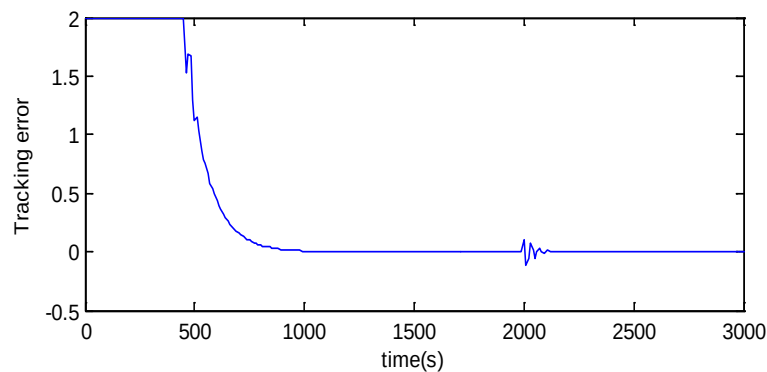


Figure 9. Tracking error curve

From the above simulation results, it can be seen that the application of sliding mode control in the tracking control of cement particle size under given interference can achieve an ideal control effect.

6. Summary

Through the data collected from the actual production process to identify the transfer functions with time delay by least squares method and then transform it to state space equation. Selecting a new state variable to remove the effect of time delay and then transform it to an error state space equation for the design of sliding mode tracking control. Designing sliding mode law and analyze the stability condition

of sliding mode. The simulation results show that the use of sliding mode control can effectively overcome the influence of interference.

7. Acknowledgement

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8. References

- [1] Wang Y, Lingling X U. Research Progress of the Influence of Particle Size Distribution on the Properties of Cement [J]. Materials Review, 2010, 24 (12): 68-71.
- [2] Yuan Z, Zhang Q, Zhang X, et al. Modeling for cement combined grinding system with closed grinding process based on LS-SVM in typical working condition[C]// IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems. IEEE, 2015: 1050-1055.
- [3] Zhang X, Yuan Z, Zhang Q, et al. T-S fuzzy modeling for cement combined grinding system via working condition template[C].The Chinese Control and Decision Conference. IEEE, 2015: 4727-4732.
- [4] Liu H, Yuan Z, Zhang Q, et al. Online Modeling for Combined Cement Grinding System via Extreme Learning Machine[C].IEEE International Conference on Information and Automation. 2015: 1452-1456.
- [5] Yuan Z, Liu H, Zhang Q, et al. Adaptive PID Control for Cement Particle Size System Based on Data-Driven Technology[C]// International Conference on Intelligent Human-Machine Systems and Cybernetics. IEEE, 2016.
- [6] Hou J, Yuan Z, Zhang Q, et al. Sliding mode control for cement combined grinding system via least square modeling[C]// IEEE International Conference on Information and Automation. IEEE, 2015: 541-546.
- [7] Young P C. Optimal Identification and Estimation of Continuous-Time Transfer Function Models [J]. 2011.
- [8] Utkin V I. Sliding Modes in Control and Optimization [J]. Communications & Control Engineering, 1992, 189 (3): 1372-9.
- [9] Yan W J, Qin W. Modeling and Control Optimization in Cement Vertical Roller Mill Process [J]. Control Engineering of China, 2012.
- [10] Skretting K, Engan K. Recursive Least Squares Dictionary Learning Algorithm [J]. IEEE Transactions on Signal Processing, 2010, 58 (4): 2121-2130.
- [11] Liu J K, Sun F C. Research and development on theory and algorithms of sliding mode control [J]. Control Theory & Applications, 2007, 24 (3): 407-418.
- [12] Yang M I, Huang J X, Wen-Lin L I. Variable Structure Control for Multi-input Discrete Systems with Control Delay [J]. Control & Decision, 2006, 21 (12): 1425-1428.
- [13] Liu J, Wang X. Discrete Sliding Mode Control [M]// Advanced Sliding Mode Control for Mechanical Systems. 2011: 97-110.
- [14] Wen-Lin L I. Guaranteed Cost Variable Structure Control for Multi-input Discrete Systems with Control Delay [J]. Journal of System Simulation, 2008, 20 (18): 4932-4936.
- [15] Swanson D A, Tayman J. Extrapolation Methods [J]. Interdisciplinarity in Engineering, 2012, 15 (2): 123-131.