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Design and Implementation of a Mould Level Control System*

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Abstract: A simple effective intelligent mould level control method is presented. It consistes of a nonlinear controller, for sliding valve and its hydraulic actuator based on model reduction and inner model control, a feed forward tundish weight controller and a mould level predictive fuzzy controller. Its accuracy and reliability for practical use in continuous casting process are demonstrated by satisfactory experimental and on-line control performances.

Key words: mould level; intelligent control; cascade control; fuzzy predictive control

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结晶器液位控制系统的设计与实现

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摘要:提出了一种简单有效的结晶器液位智能控制控制方法,它包括一个基于模型降阶和内模控制的非线性滑动水口及其液压机构控制器、一个中间包重量前馈控制器和一个结晶器液位模糊预测控制器.实验和现场使用表明,该方法能够准确可靠地应用于连铸过程控制之中.

关键词:结晶器液位;智能控制;串级控制;模糊预测控制

1 Introduction

Mould level control is very important in continuous casting process. It is realized by controlling the flow rate of liquid steel from the tundish into the mould via a hydraulic servo system. Fluctuation of mould level may not only degrade slab quality, but also lead to overflow or leakage of liquid steel. There are many problems with mould level control owing to the extraordinarily high temperature environment, such as: 1) disturbances and dynamics not included in the model; 2) time varying and nonlinear behavior owing to sliding valve abrasion or blockage; 3) large system delay; and 4) high frequency measurement noises. For these reasons, it's impossible to describe and control mould level system accurately with traditional modeling and control method. Recently, intelligent methods such as predictive control[1] and fuzzy control[2~4] have been used in continuous casting process. But none of them can satisfactorily reject the effect of casting speed, nor can they perform robust mould level control. On the basis of our previous researches[5~7], an intelligent mould level control method is presented in this paper. It was implemented in a Chinese Ninth 5-Year Plan Project of an iron and steel plant. Satisfactory performance was reported in both experiments and real-time casting process.

2 Cascade mould level controller design

The structure of the mould level control system is shown in Fig. 1. Wherein nonlinear controller C_4 is designed to compensate for the effect of nonlinear flow behavior of the sliding valve; feed forward controller C_3 is designed to distract the effect of tundish weight on the level; C_2, which is based on model reduction and inner model control, is designed for sliding valve and its hydraulic actuator; and controller C_1 is mould level predictive fuzzy controller to reject disturbances caused by casting speed and dynamics not modeled.

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2.1 Valve flow nonlinear controller

The valve contains smooth nonlinearities including valve geometry, flow dynamics, and erosion caused by high temperature liquid steel.

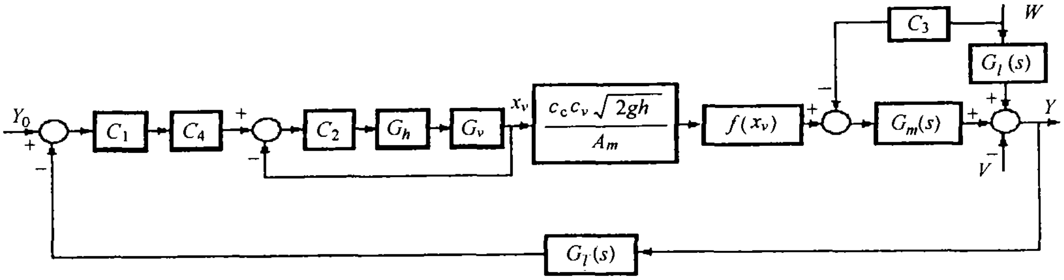

Fig. 1 Mould level control system

Dithering is often used in practical level control to compensate for these nonlinearities. But this may speed up valve wornout and shorten its life span. So according to the structural characteristics of the valve and its behavior, the following nonlinear controller is designed for it

$$C_4 = K_n g(x_v), \tag{1}$$

where K_n inverts the gain of the valve flow rate system, namely

$$K_n = \frac{A_m}{c_c c_v \sqrt{2gh}}. \tag{2}$$

And $g(x_v)$ is used to compensate for the nonlinear geometry of the valve, namely $g(x_v)$ inverts the function $f(x_v)$ between valve position and valve effective flow area. $f(x_v)$ can be obtained easily according to basic knowledge of physics and geometry as

$$f(x_v) = \pi r^2 - 2r^2 \arcsin\left(\frac{q - x_v}{2r}\right) - (q - x_v)\sqrt{r^2 - \frac{(q - x_v)^2}{4}}. \tag{3}$$

2.2 Tundish weight feed forward controller

Tundish weight can be measured very easily. It is related to mould level by a transfer function $G_t(s)$ which is known. So the following feed forward controller C_3 is used to remove its effect on mould level

$$- WC_3 G_m(s) + WG_t(s) = 0. \tag{4}$$

2.3 Sliding valve position controller

The open loop system comprising sliding valve and its hydraulic servomechanism is a high order system. Thus the controller design follows a model reduction process. And the well-known inner model control (IMC) strategy is used on the basis of the reduced model to obtain the following auto-tuning PID controller C_2

$$G_c(s) = \frac{F(s)\tilde{G}_{\text{inv}}(s)}{1 - F(s)\tilde{G}_{\text{inv}}(s)\tilde{G}(s)}. \tag{5}$$

It is usually true that mould level oscillates at a high frequency, thus there are dithers in the adjusting action of the valve. To avoid these dithers, valve position output is used instead of the error of valve position in the differential term of this controller. Then the valve position actuator set point (relating directly to mould level) is excluded from the differential term of C_2, so the control output derivative kick caused by step change of set point is avoided. This in turn makes the adjustment of the valve very smooth.

2.4 Fuzzy predictive mould level controller

The mould level controller C_1 is designed by combining fuzzy control method and predictive approach. Here fuzzy control plays the main role and level prediction acts only as a reinforcement of fuzzy control. This controller is carefully designed to reject the disturbances of measurement noises and the noise caused by casting speed and dynamics which are not modeled, and to improve robustness and steady state behavior of the system.

The partitioning of the universe of discourse in fuzzy control is determined in accordance with the practical process requirement of this iron and steel plant, and the fuzzy control rulebase is a collection of weighted rules in the form

If error is E_i and rate is E_{ej},
then output is U_{ij}.

Using this rulebase and other expert rules, the optimal fuzzy control action is obtained.

To adjust the fuzzy control rules, a mould level fuzzy prediction model is built up

$$\hat{y} = \frac{\sum_{i=1}^{m} \{\min[\mu_{A_1^i}, \mu_{A_2^i}, \cdots, \mu_{A_n^i}] \cdot y^i \cdot \omega^i\}}{\sum_{i=1}^{m} \min[\mu_{A_1^i}, \mu_{A_2^i}, \cdots, \mu_{A_n^i}]},$$

where ω^i 's are weights. The parameters in this model are identified with least mean square (LMS) strategy. And most importantly, the control rules are refined by this means. Then after defuzzification, fuzzy controller output uk is finally obtained.

Although the rules are refined, the fuzzy controller may still be unsatisfactory in the existence of colored noise. For this reason, a robust predictive controller is designed to reinforce the fuzzy controller. In the design of this predictive controller, an equalization process is introduced for the following CARIMA mould level model with colored noise

$$A(z^{-1})y(t) = B(z^{-1})u(t-d) + \frac{C(z^{-1})}{\Delta}w(t), \tag{6}$$

where $A(z^{-1})$, $B(z^{-1})$ and $C(z^{-1})$ are coefficient polynomials, and $A(z^{-1})$ is monic, $\Delta = 1 - z^{-1}$ represents the integrating characteristic of the mould, $y(t)$ and $u(t-d)$ are system output and control signal respectively, and $w(t)$ is the colored noise.

Before the prediction of level output and the optimal control law can be obtained, the process model is reformed on the basis of the following linear relationship according to the representing theorem

$$\begin{cases} \dot{\Psi}(t) = H(t)\Psi(t) + \xi(t), \\ \Psi(t_0) = \Psi_0, \end{cases} \tag{7}$$

where $\Psi(t) = C(z^{-1})w(t)$.

It represents the colored noise of the mould level system. Define

$$\xi'(t) = \Psi(t) - \xi(t).$$

This term is called the equalized white noise of the colored system noise. Then the process model (6) reads as follows

$$A(z^{-1})y'(t) = B(z^{-1})u'(t-d) + \xi'(t)/\Delta, \tag{8}$$

where the equalized output term and control term are

$$y'(t) = H(t)y(t), \tag{9}$$

$$u'(t) = H(t)u(t). \tag{10}$$

In addition, dynamic filtering is included in the cost function to remove the influence of measurement noises. Then GPC strategy is used on the equalized model to obtain the CGPC control $\hat{u}$.

This process amounts to introducing the following cost function

$$J_f = \mathrm{E}\left\{\sum_{j=d}^{N_p}\gamma\left[\hat{y}^{\text{forc}}_{t+j} + \frac{f_n(z^{-1})}{F_d(z^{-1})}\hat{y}^{\text{free}}_{t+j} - r_{t+j}\right]^2 + \sum_{j=0}^{N_u-1}\lambda[\Delta u_{t+j}]^2\right\}. \tag{11}$$

By minimizing this cost function, we obtain the optimal control law of the equalized system

$$\hat{u}' = [\gamma G^{\mathrm{T}}G + \lambda I]^{-1}\gamma G^{\mathrm{T}}\left[r - \frac{F_n}{F_d}p'\right]. \tag{12}$$

Finally, combine the equalizing equations (8) and (9), the optimal prediction and control law of the initial mould level control system are obtained

$$\hat{y} = H^{-1}\hat{y}' = H^{-1}G\hat{u}' + H^{-1}p', \tag{13}$$

$$\hat{u} = H^{-1}\hat{u} = H^{-1}[\gamma G^{\mathrm{T}}G + \lambda I]^{-1}\gamma G^{\mathrm{T}}\left[r - \frac{F_n}{F_d}p\right]. \tag{14}$$

The combination of this predictive control signal $\hat{u}$ with fuzzy controller output uk results in the final mould level controller C_1, namely

$$u(k) = \begin{cases} 0, & |y(k) - y_0| < e_1, \\ \hat{u}, & y(k) - y_0 < 0, \\ & e_1 \leqslant |y(k) - y_0| < e_2, \\ a \cdot uk + (1-a)\hat{u}, & y(k) - y_0 > 0, \\ & e_1 \leqslant |y(k) - y_0| < e_2. \end{cases} \tag{15}$$

3 Experiment and engineering implementation

3.1 Experiment

In the experiment, the cascade PID controller in [8] was compared with the method suggested in this paper. The step responses are shown in Fig.2, performance 1 is the new method. From Fig.2 we can see, when conventional PID controller is used, mould level oscillates violently and large level overshoot occurs. When under the control of the new method, mould level arrives at its set point quickly. The robustness of level system is also remarkably improved, no oscillations are found.

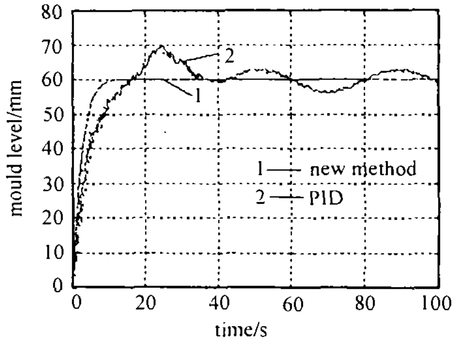

Fig. 2 Control performance in experiment

3.2 Engineering implementation

The slab caster studied in this paper has a camber radius of 3000mm. Its normal casting speed is 1 ~ 3 m/min. The mould of this caster has a cross section of 150 cm × 150 cm, and its length is $L = 30$cm. The mould oscillates with a frequency $f = 1.25 \sim 6.7$Hz and multitude ± 3mm. The maximum driven force of the rolls is $F = 200$kN. According to practical process requirement, mould level error should be less than 10mm, and with no acute fluctuation. Fig.3 shows the level performance in real casting line under the control of the method presented in this paper. It's clear that the maximum level error is about 5mm, and level fluctuation multitude is small.

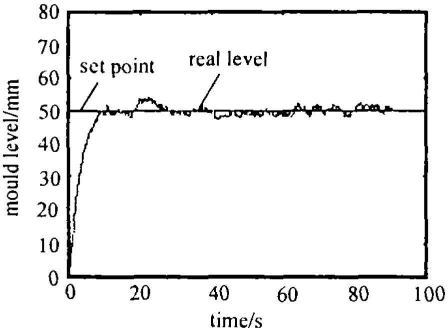

Fig. 3 Real time control performance

When the changes of casting speed occurs or during tundish changeover period, the automatic control methods presently in use are not capable of following mould level set point. In such cases, operators usually have to switch to manual control mode. This in turn causes acute fluctuation of mould level. Studies were carried out for dealing with these two cases in the implementation of this new method. It turned out that when casting speed was increased, mould level decreased, then it returned to its set point quickly. This process lasted for a period of time owing to process inertia. But no extraordinarily large level errors were found. The most serious error was less than 10mm. The approximately same phenomenon occurred during the changeover of tundish. As to why large mould level errors did not occur, it is important to point out that anti-integral-windup strategy was included in the suggested new controller during implementation. The integration of the sliding valve controller was canceled when the absolute error was large enough.

4 Conclusions

An inner loop valve position auto-tuning PID controller is designed on the basis of the inner model control and model reduction. It makes the valve work very smooth and fast. In addition, tundish weight and valve nonlinearity are respectively compensated with feed forward control and nonlinear control. And most importantly, mould level is satisfactorily controlled using a fuzzy controller reinforced by a CGPC strategy that can remove the influence of the colored noises caused mainly by casting speed. Thus the robustness and stable state performance of mould level system are remarkably improved. This new control strategy can be used not only in the case of normal casting process, but also in the start-up and finishing period of continuous casting.

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