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Research Article

Adaptive Fuzzy plus Integral Control for Double Variable Electric Furnace

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Abstract: The vertical electric furnace is a dual input and output temperature system with features of large delay, strong coupling. Traditional control algorithm is difficult to meet the control requirements. Based on these features, the study proposes decoupling and adaptive fuzzy plus integral control strategy. The experiments show that the decoupling and intelligent adaptive fuzzy control algorithm is more robustness and anti-interference.

Keywords: A fuzzy control, double variable electric furnace, decoupling control

INTRODUCTION

Temperature is one of the basic modern industrial control parameters. And the object of the temperature control system generally has some features, such as non-linear, strong coupling and time delay. Since the 20th century, with the rapid development of science and technology and the increasingly high demand for the quality and performance of thermal processing products, people are increasingly active in research control thermal methods of the machining process (Bai *et al*., 2008; Li *et al*., 2012).

Fuzzy logic control is an important branch of artificial intelligence theory. In 1965, since L.A. Zadeh, who is a control theorist, proposed the theory of fuzzy set in order to describe the fuzzy things (Matsuda *et al*., 1990). Fuzzy control technology has been widely used in process control.

In a fuzzy control system, the fuzzy controller affect the control performance of system and the fuzzy controllers' performance, to a large extent, depends on the determination and adjustment of fuzzy control rules. Different weighting of the input variables of the size of the means of the factors K_e and K_{ec}extent, while in the adjustment of the system characteristic, K_e and $K_{ec}$are mutual constraints.

Lasting high temperature testing machine–vertical electric furnace is a dual input and output temperature system. The system presents such character: big thermal inertia and long decrease time because of its physical design. The traditional PID control mode cannot achieve very good control effect. In order to meet the industry requirements well, the study proposes decoupling and adaptive fuzzy plus integral control algorithm to improve the furnace temperature control effect.

DESIGN OF ELECTRIC FURNACE TEMPERATURE CONTROL SYSTEM

Introduction of vertical electric furnace: This design by typical temperature field controlled member-electric furnace as the controlled member. This electric furnace is double inputs and outputs system which need to decouple and the system presents the dissymmetry of decoupling. Because the quantity of heat of heating wire must pass through such bad heat transfer media, so its thermal inertia is very big. The entire furnace temperature system shows the characteristics of non-linear, strong coupling and large time delay.

The heating furnace comprises two groups of 750W electric heating wire which is wound on the porcelain bushing as dual input. The porcelain bushing middle hovering flight the steel test specimen and steel jig and the two K(EU-2) indexing numbers armor type thermo-elements as the double outputs is installed at the steel test specimen surface in the distance of 25mm. The electric furnace structure is shown in Fig. 1.

The structure design of fuzzy control system: Considering the physical characteristics of the electric furnace, the design is divided into the decoupling controller design and the fuzzy plus integral controllers design. So the system is composed of fuzzy plus integral controllers, decoupling controller and controlled member showed in Fig. 2 (Fu and Chai, 2009; Li and Jiang, 2008; Zhang *et al*., 2010).

The system is a double inputs and double outputs control system. After the decoupling controller, the control system is decomposed into two independent fuzzy control systems.

Design of decoupling controller: Decoupling problem is an important part of MIMO linear system theory. The

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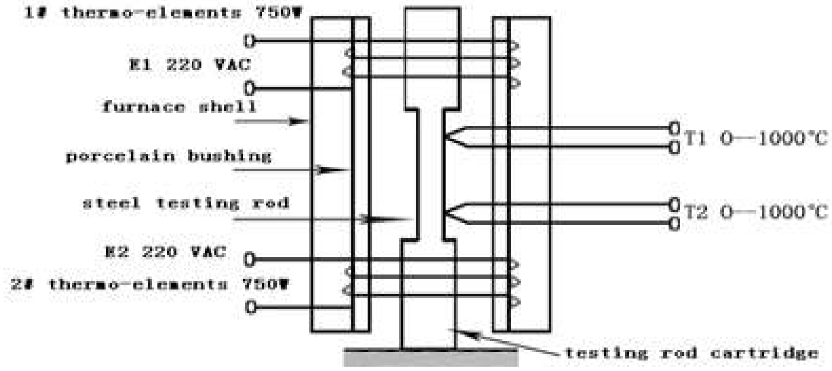

Fig. 1: Structure of the electric furnace

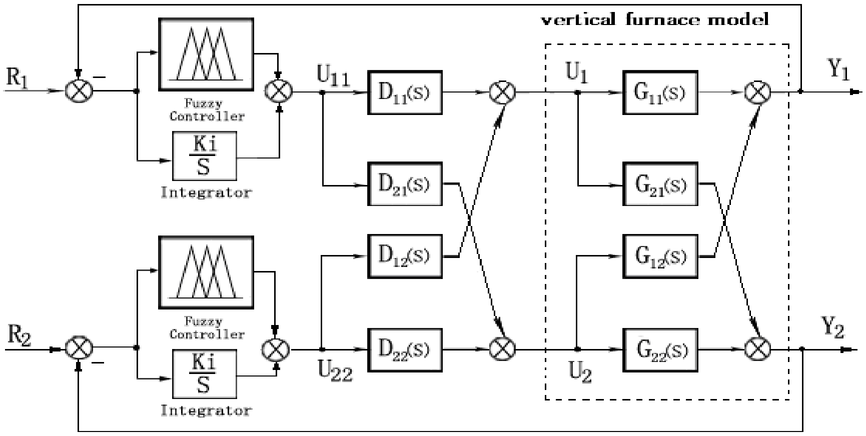

Fig. 2: The structure of fuzzy control system

goal of decoupling control is to eliminate complicated loop interactions so that a change in one process variable will not cause corresponding changes in other process variable. In this scheme, a compensation network called a decoupler is used right before the process. This decoupler is the inverse of the gain array and allows for all measurements to be passed through it in order to give full decoupling of all of the loops.

- **Analysis of decoupling system:** A linear time invariant deterministic continuous-time multivariable system with p outputs y, m inputs u and n states x can be described as state-space system [A, B, C, D]:

$$\left.\begin{aligned} \dot{X} &= AX + BU \\ Y &= CX \end{aligned}\right\} \tag{1}$$

The system in this study is a dual input and output system and the state-space system can be described as follow:

$$\left.\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u \\ y &= \begin{bmatrix} C_1 & C_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{aligned}\right\} \tag{2}$$

The control rule scheme adopts input transform and combining state feedback:

$$u = Rv - Fx = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} - \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{3}$$

where, u is 2 dimensional reference input vector, [F, R] are matrices of dimensions, called $\{F, R\}$.

And the closed-loop system equation of state and output equation can be deduced as follow:

$$\left.\begin{aligned} \dot{x} &= (A - BF)x + BRv \\ y &= Cx \end{aligned}\right\} \tag{4}$$

Called $\sum_{F,R}(A - BF, BR, C)$.
Closed-loop system's transfer function matrix is:

$$G_{F,R}(s) = C(sI - A + BF)^{-1}BR \tag{5}$$

If exist {F, R} that make the transfer function matrix to be a diagonal matrix, i.e.,

$$G_{F,R}(s) = \mathrm{diag}\{G_{11}(s), G_{22}(s)\} \tag{6}$$

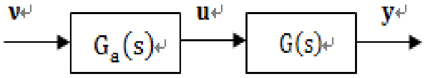

Fig. 3: The structure of forward feed compensator

Called controlled system $\sum(A, B, C)$ can be decoupled by $\{F, R\}$.

- **Realize closed-loop decoupling control with the counter system approach:** If the inverse transfer function matrix G(s) of controlled system $\sum(A, B, C)$ is exists, the forward feed compensator $G_a(s)$ and its structure diagram as shown in Fig. 3.

Supposing:

$$G_a(s) = G^{-1}(s)G_L^*(s) \tag{7}$$

where, $G_L^*(s)$ is the aim diagonal type transfer function matrix.
Supposing:

$$G_L^*(s) = \begin{pmatrix} \frac{1}{s^{\alpha_1}} & 0 \\ 0 & \frac{1}{s^{\alpha_2}} \end{pmatrix} \tag{8}$$

The relationship between input v and output y is:

$$v = y^{\alpha} = \begin{bmatrix} y_1^{(\alpha_1)} \\ y_2^{(\alpha_2)} \end{bmatrix} \tag{9}$$

Controlled system use state feedback and input transformation combination strategy to realize closed-loop decoupling control. The input component $v_i(t)$ ($i = 1, 2$) is the output component $y_i(t)$ ($i = 1, 2$) of the α_i ($i = 1, 2$) order derivative.
The output equation in system $\sum(A, B, C)$ is:

$$y_i = c_i^T x \quad (i = 1, 2) \tag{10}$$

On time t derivation:

$$\dot{y}_i = c_i^T \dot{x} = c_i^T Ax + c_i^T Bu \; (i = 1, 2) \tag{11}$$

If the row vector $c_i^T B \neq 0$, then make $\alpha_1 = 1$ and stop the derivative operator, otherwise, then the time t derivative:

$$\ddot{y}_i = c_i^T A\dot{x} = c_i^T A^2 x + c_i^T ABu \; (i = 1, 2) \tag{12}$$

If the row vector $c_i^T AB \neq 0$, then make $\alpha_2 = 2$. The time t α_i order derivative of y_i is:

$$y_i^{(\alpha_i)} = c_i^T A^{\alpha_i} x + c_i^T A^{\alpha_i - 1} Bu \; (i = 1, 2) \tag{13}$$

$$y^{(\alpha)} = \begin{bmatrix} y_1^{(\alpha_1)} \\ y_2^{(\alpha_2)} \end{bmatrix} = \begin{bmatrix} c_1^T A^{\alpha_1} \\ c_2^T A^{\alpha_2} \end{bmatrix} x + \begin{bmatrix} c_1^T A^{\alpha_1 - 1} B \\ c_2^T A^{\alpha_2 - 1} B \end{bmatrix}$$
$$u = Lx + D_0 u \tag{14}$$

where, L and D_0 are both 2×2 dimensional matrix and called decoupling matrix.

When decoupling matrix D_0 is a non-singular matrix, solves the control rule as:

$$u = D_0^{-1} v - D_0^{-1} Lx \tag{15}$$

Supposing the denominator multinomial of expectation closed-loop transfer function matrix $G_L^*(s)$ is:

$$\Delta_i^*(s) = s^{\alpha_i} \; (i = 1, 2) \tag{16}$$

Then:

$$L = \begin{bmatrix} c_1^T A^{\alpha_1} \\ c_2^T A^{\alpha_2} \end{bmatrix} = \begin{bmatrix} c_1^T \Delta_1^*(A) \\ c_2^T \Delta_2^*(A) \end{bmatrix} \tag{17}$$

After using the control strategy of input transformation and state feedback matrix, the closed-loop system $\sum_{F,R}(A - BD_0^{-1}L, BD_0^{-1}, C)$ realizes the decoupling control.

Design of fuzzy controller: A fuzzy control system is based on fuzzy logic. The advantage of fuzzy logic is that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

Fuzzy controller consists of an input stage, a processing stage and an output stage. The input stage maps sensor or other inputs to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value.

The two inputs of system are shown as the error e and the change-in-error of the system, respectively and the outputs is shown as u. The universe of discourse of variables take {-6, -5, - 4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, }. Introduction quantification factor K_e and K_{ec} transform error e and the change-in-error ec into the universe of discourse of fuzzy controller. Variables e, ec and u in this system can be subdivided into a range of states: {PB, PS, ZO, NS, NB}. The membership function chooses triangle function, its mathematical expression is:

Table 1: Control rules

Ec/e	NB	NS	ZR	PS	PB
NB	PB	PS	PS	ZR	NS
NS	PB	PS	PS	ZR	NS
ZR	PS	PS	ZR	NS	NB
PS	PS	ZR	NS	NS	NB
PB	PS	ZR	NS	NS	NB

$$\mu_{\underset{\sim}{A}_i}(x) = \begin{cases} \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

Summarizes the control rule according to the experience of human control expert, the control rules can be inferred based on the rule of IF E is A_i and EC is B_i $(i = 1, 2)$ by the Mamdani inference method. Considering adapting to the requirements of the controlled object, introducing adjustment factor $\alpha_i (i = 0, 1, 2)$ for each error level, the control rules with adjustment factor are as follow:

$$U = \begin{cases} -\langle \alpha_0 E + (1-\alpha_0) EC \rangle, & E = ZR \\ -\langle \alpha_1 E + (1-\alpha_1) EC \rangle, & E = NS, PS \\ -\langle \alpha_2 E + (1-\alpha_2) EC \rangle, & E = NB, PB \end{cases} \tag{19}$$

where, α_i $(i = 0, 1, 2)$are weighted coefficient.
When $\alpha_i = \{0.4, 0.6, 0.75\}$
The control rule table as shown in Table 1.

Extracts the precise output control quantity based on the weighted mean method:

$$U^* = \left(\frac{\sum_i u_c^*(U_i) U_i}{\sum_i u_c^*(U_i)} \right) \tag{20}$$

Experiments: Unit step signal is applied to the input terminals of the vertical furnace, then gather data from the two outputs of the temperature signal every 5 minutes, collected a total of 280 sets of data. Through data processing, mathematical model is established by using experimental method.
System transfer function:

$$G(S) = \begin{bmatrix} \frac{2.1}{402s+1} e^{-114s} & \frac{1.4}{714s+1} e^{-114s} \\ \frac{13.1}{2016s+1} e^{-78s} & \frac{17.5}{1662s+1} e^{-78s} \end{bmatrix} \tag{21}$$

When reference input

$$R_1 = \begin{cases} 1, & t \ge 0 \\ 0, & t < 0 \end{cases} \quad R_2 = \begin{cases} 0.5, & t \ge 0 \\ 0\ , & t < 0 \end{cases}$$

And quantification factors are, respectively

$$K_e = 0.5, K_{ec} = 1, K_u = 0.1$$

The response curve of fuzzy control system is shown as Fig. 4.

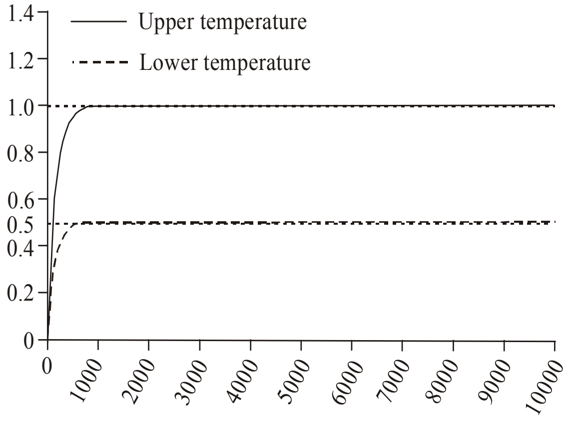

Fig. 4: Response curve of fuzzy control system

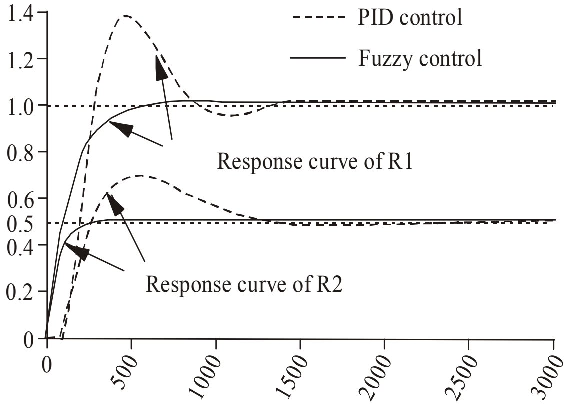

Fig. 5: Control effect comparison between PID algorithm and Fuzzy plus Integral algorithm

After decoupling, two inputs have not had the influence to the output of opposite part, the entire temperature control system could be regarded as two independent temperature control systems and the system has realized the complete decoupling.

The temperature control system based on fuzzy control rules in the step response of the input conditions, the output of the system does not exist overshoot and has smaller steady-state error, the algorithm avoid the phenomenon of out-of-control because of its thermal inertia.

- **Comparison with PID algorithm:** Carrying on the fuzzy control and PID control to the system separately, the response curve is shown in Fig. 5.

From the experiment, for large time delay, nonlinear and strong coupling system, fuzzy control algorithm for the control effect is much better than PID control algorithm. Especially in this typical temperature system, its strong thermal inertia characteristics increased the difficulty of control and the proposed adaptive fuzzy control plus integral control system design is a good solution to the problem.

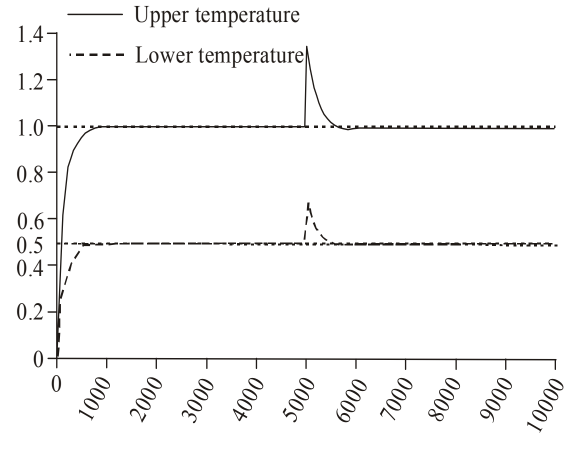

Fig. 6: Robustness analysis

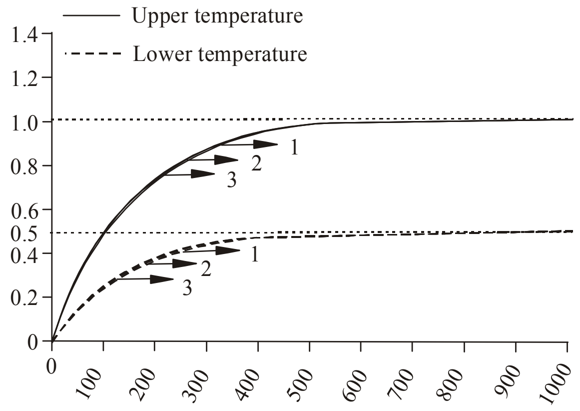

Fig. 7: Anti-interference analysis

- **Robustness:** Due to the model has some error, make the system model parameters increase to 20 and 20% lower, in order to analyze the controller robustness and compare with the original output curves. The response curve is shown as Fig. 6.

When the parameter of system model has perturbation±20%, the system can still maintain the good stability as well as the control effect. Obviously, regarding the non-linear and strong coupling system, the control algorithm of fuzzy logic rule-based has good robust performance. Where curve 2 is the original curve and curve 1 and curve 3 represent the curve when the parameter of system model has perturbation 20 and-20% respectively.

- **Anti-interference performance:** Joining the step signal perturbation to the system, which peak-to-peak value is 40% of input. The response curve is shown as Fig. 7.

CONCLUSION

Compared with PID algorithm, the fuzzy control algorithm has better dynamic property and stable state performance, the characters of strong robustness and anti-jamming even more suits the request of such temperature system. The fuzzy algorithm provides a solution to solve such control problem of non-linear, strong couple and large delay.

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