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Real Time Temperature Prediction Method of Furnace by New Fuzzy Modeling Method and Its Realization

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Abstract We discovered the defect through researching about previous modeling technology[1, 2] and resolved the rank lack problem requested in calculation of 30－40th dimensional matrix. Then we proceeded the furnace temperature prediction examination by a way of real time fuzzy prediction modeling method applying new fuzzy reasoning theory [3, 4], and then by comparing with previous temperature prediction temperature [5－7], verified the effectiveness of proposed method.
In this paper we applied the new fuzzy modeling method proposed by us and established the furnace temperature prediction model, and then compared with previous temperature prediction methods through simulation experiments and field experiments and evaluated its effectiveness.
Key words fuzzy modeling, predication model, fuzzy reasoning method, move rate

Introduction

In the paper[2], for solving the problem of the real time temperature predication problem is provided an adaptive identification algorithm based on regressive model. But the regressive model that characteristics of the furnace is represented only a formula have difficulty in the modeling of nonlinearity of the objects(furnaces) and have accuracy of about 85%. There are a lot of researches methods of modeling of the nonlinear objects, in the paper[4] is proposed a fuzzy modeling method based on fuzzy reasoning method[5] and then verified its effectiveness. However the fuzzy modeling method of the paper[4] is impossible to use it conclusion parameter estimation.

Otherwise in the papers[8, 9] is proposed a fuzzy identification algorithm for temperature predication of furnace and realized predication of only 3hours. But in the indusial processes are used 3 sensors for the 1 furnace and accuracy of predication model lows.

In this paper, to overcome disadvantages of the past papers[2, 8, 9], the fuzzy reasoning method based on the move rate of the papers[3, 6, 7] is used in the fuzzy model identification and proposed a new method of real time temperature predication of the furnace and then compared with past methods throw simulation and test of furnaces and then verified its effectiveness.

1. Fuzzy Modeling Method by New Product Reasoning

1.1. Definition of move rates for s-type, z-type and trapezoid membership

In case of s-type, z-type and trapezoid member, the move rates d_{ij} for input information x_{j0} are all defined as equation as equation (1), (2) and (3).

$$d_{ij}=\begin{cases}0, & \text{if } x_{j0}\le x_{cij}\\ \dfrac{x_{j0}-x_{cij}}{x_{rij}-x_{cij}}, & \text{if } x_{rij}>x_{j0}\ge x_{cij}\\ 1, & \text{if } x_{rij}\le x_{j0}\end{cases} \tag{1}$$

$$d_{ij}=\begin{cases}0, & \text{if } x_{j0}\ge x_{cij}\\ \dfrac{x_{cij}-x_{j0}}{x_{cij}-x_{lij}}, & \text{if } x_{lij}\le x_{j0}\le x_{cij}\\ 1, & \text{if } x_{j0}\le x_{lij}\end{cases} \tag{2}$$

$$d_{ij}=\begin{cases}1, & \text{if } x_{1ij}>x_{j0} \text{ or } x_{4ij}\le x_{j0}\\ \dfrac{x_{2ij}-x_{j0}}{x_{2ij}-x_{1ij}}, & \text{if } x_{1ij}\le x_{j0}\le x_{2ij}\\ 0, & \text{if } x_{2ij}\le x_{j0}\le x_{3ij}\\ \dfrac{x_{j0}-x_{3ij}}{x_{4ij}-x_{3ij}}, & \text{if } x_{3ij}\le x_{j0}\le x_{4ij}\end{cases} \tag{3}$$

1.2. Recursive matrix making procedure of T-S fuzzy model based on product reasoning

Step 1: For input information x_{j0}, get the move rates d_{ij} by equation (1)–(3).

Step 2: Get the product term d_i of each rule as equation (4).

$$d_i=1-[d_{i1}\wedge d_{i2}\wedge\cdots\wedge d_{in}],\quad i=\overline{1,\ m}\quad j=\overline{1,\ n} \tag{4}$$

Step 3: Calculate the rest $\hat{d}^i$ of each rule affecting to output by equation (5).

$$\hat{d}^i=d_i\Big/\sum_{i=1}^{n}d_i \tag{5}$$

Step 4: For fuzzy model output y^0 as equation (6), calculate the recursive matrix Z by equation (7).

$$y^0=\sum_{i=1}^{n}\widehat{w}^i y^i=\sum_{i=1}^{n}(a_0^i z_0^i+a_1^i z_1^i+\cdots+a_m^i z_m^i) \tag{6}$$

$$Z=\begin{pmatrix} z_0^{1(1)} & \cdots & z_m^{1\,(1)} & z_0^{2(1)} & \cdots & z_m^{2\,(1)} & \cdots & z_0^{n(1)} & \cdots & z_m^{n\,(1)}\\ z_0^{1(2)} & \cdots & z_m^{1\,(2)} & z_0^{2(2)} & \cdots & z_m^{2\,(2)} & \cdots & z_0^{n(2)} & \cdots & z_m^{n\,(2)}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ z_0^{1(p)} & \cdots & z_m^{1\,(p)} & z_0^{2(p)} & \cdots & z_m^{2\,(p)} & \cdots & z_0^{n(p)} & \cdots & z_m^{n\,(p)} \end{pmatrix} \tag{7}$$

1.3. Fuzzy modeling method based move rates

Proceed T-S fuzzy modeling with input output data. Denoting the coefficient of equation (6) with a vector

$$A=(a_0^1 \cdots a_m^1\ a_0^2 \cdots a_m^2 \cdots a_0^n \cdots a_m^n)^T . \tag{8}$$

T-S fuzzy model equation (9) is denoted with equation (10) simply.

$$R^i : \text{if} \quad x_1 \text{ is } A_1^i,\ x_2 \text{ is } A_2^i,\ \cdots,\ x_m \text{ is } A_m^i \quad \text{then} \quad y^i = a_0^i + \sum_{j=1}^{m} a_j^i x_j \tag{9}$$

where $x^0 = [x_1^0,\ x_2^0,\ \cdots,\ x_m^0]^T$: input vector, a_j^i : j th antecedent fuzzy set of i th rule ($i=\overline{1,\ n},\ j=\overline{1,\ m}$), $R^i(i=\overline{1,\ n})$: i th object rule, y^i : conclusion value of R^i

By fuzzy reasoning, the set $y=[y_1,\ y_2,\ \cdots,\ y_p]^T$ of real output value of p may be expressed as equation (10).

$$y = ZA + \varepsilon \tag{10}$$

where p is the number of input output data couples, $z_j^{i\,(k)}(i=\overline{1,\ n},\ j=\overline{0,\ m},\ k=\overline{1,\ p})$ is k th z_j^i value. z_j^i is denoted as equation (11) and $\varepsilon=[\varepsilon_1,\ \varepsilon_2,\ \cdots,\ \varepsilon_p]^T$ is corresponding error vector.

$$\left.\begin{aligned} z_0^{i\,(k)} &= \hat{d}^i \\ z_j^{i\,(k)} &= \hat{d}^i x_j^{0(k)} \end{aligned}\right\}, \quad i=\overline{1,\ n}, \quad j=\overline{1,\ m}, \quad k=\overline{1,\ p} \tag{11}$$

where $x_j^{0(k)}$ is j th element of k th input vector. n is the number of rules, m is the dimension of input information, p is the number of input output data couples. Construct the recursive matrix by using fourth step of product reasoning.

Estimation equations proposed in reference[1] contradict and it is impossible to use it conclusion parameter estimation. Because θ_k in equation (12) is row vector and $F_k(y_k - H_k\theta_{k-1}^T)$ is column vector, so that it is impossible to proceed matrix add.

$$\theta_k = \theta_{k-1} + F_k(y_k - H_k\theta_{k-1}^T) \tag{12}$$

$$F_k = \frac{S_{k-1}H_k^T}{1+H_kS_{k-1}H_k^T} \tag{13}$$

$$S_k = S_{k-1} - F_kH_kS_{k-1} \tag{14}$$

where θ_k is parameter vector to estimate, S_k is standard deviation matrix, H_k is data vector defined as below equation (15).

$$\begin{aligned} H_k = (&W_k{}^1,\ W_k{}^1x_{1k},\ \cdots,\ W_k{}^1x_{mk},\ W_k{}^2,\ W_k{}^2x_{1k},\ \cdots, \\ &W_k{}^2x_{mk},\ \cdots,\ W_k{}^n,\ W_k{}^nx_{1k},\ \cdots,\ W_k{}^nx_{mk}) \end{aligned} \tag{15}$$

The result that investigate conclusion parameter estimation equation of reference [1] and get new estimation equation are as follows.

For dynamic T-S fuzzy system represented as equation (16), conclusion parameter vector is represented as equation (17).

$$
\begin{aligned}
R^i: &\text{ if } y(k-1) \text{ is } A_1^i,\ y(k-2) \text{ is } A_2^i,\ \cdots,\ y(k-n_y) \text{ is } A_{n_y}^i, \\
&u_1(k-t_{d1}) \text{ is } A_{n_y+1}^i,\ \cdots,\ u_1(k-t_{d1}-n_1) \text{ is } A_{n_y+n_1+1}^i,\ \cdots, \\
&u_p(k-t_{dp}) \text{ is } A_{n_y+n_1+\cdots n_{p-1}+p}^i,\ \cdots, u_p(k-t_{dp}-n_p) \text{ is } A_{n_y+n_1+\cdots+n_p+p}^i, \\
&\text{then } y^i(k) = a_0^i + a_1^i y(k-1) + a_2^i y(k-2) + \cdots + a_{n_y}^i y(k-n_y) + \\
&+ a_{n_y+1}^i u_1(k-t_{d1}) + \cdots + a_{n_y+n_1+1}^i u_1(k-t_{d1}-n_1) + \cdots + a_{n_y+n_1+\cdots+n_{p-1}+p}^i \\
&u_p(k-t_{dp}) + \cdots + a_{n_y+n_1+\cdots+n_p+p}^i u_p(k-t_{dp}-n_p)
\end{aligned}
\tag{16}
$$

where R^i is i^{th} fuzzy rule, A_j^i is j^{th} fuzzy subset of R^i, y^i is conclusion reasoning output value, a_j^i is conclusion parameter, $u_1(\cdot)$, $\cdots$, $u_p(\cdot)$ is input variable, $y(\cdot)$ is output variable, k is time variable.

$$\theta_k = \theta_{k-1} + (y_k - H_k \theta_{k-1}{}^T)^T H_k S_k{}^T \tag{17}$$

where $S_k = S_{k-1} - F_k H_k S_{k-1}$, $F_k = \dfrac{S_{k-1} H_k{}^T}{1 + H_k S_{k-1} H_k{}^T}$ and H_k is represented as equation (15).

2. Temperature Prediction Model Making of Furnace and Verification

For making Temperature prediction model of furnace, we proceeded as following steps.

① Measure the temperature of furnace by thermocouple and construct the database set of input and output by extracting voltage and current data server.

② Applying this proposed fuzzy modeling method on this database set, make the temperature prediction model and evaluate its correctness by comparing with previous fuzzy modeling method.

③ Evaluate whether made temperature prediction model represent the temperature characteristic of furnace correctly or not and verify its validity.

Fuzzy modeling program for making the temperature prediction model is programmed by MATLAB and the real time temperature prediction of furnace by this temperature prediction model is realized by C++. By applying dynamic T-S fuzzy modeling method based product reasoning, we made the temperature prediction model of 60 furnaces.

Fig. 1 shows the output value of temperature prediction model and real value for furnace No 2.

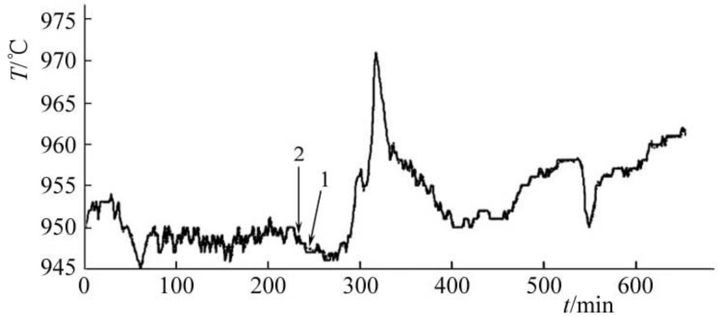

Fig. 1. Model output value by MATLAB and real value of furnace No 2

In Fig. 2, the accuracy of model is 99. 86% and mean error between model output and real value is 0.315℃.

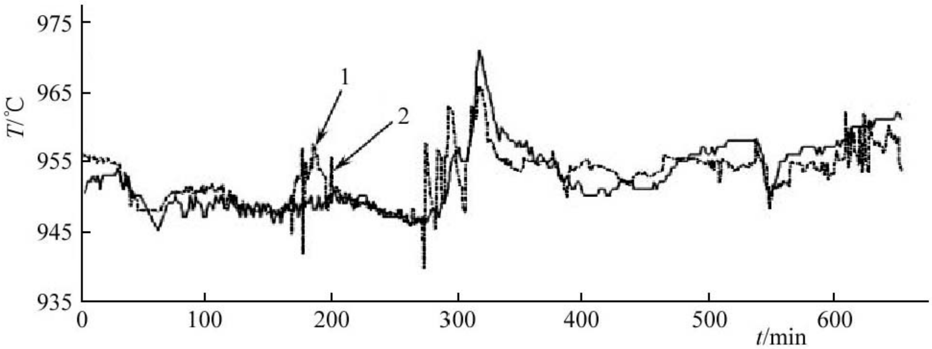

Fig. 2. Output value of model got by ANFIS and real value (Furnace No. 2)

Fig. 2 shows the output value of fuzzy model got by ANFIS and real output value in furnace No 2. The accuracy of model of Fig. 2 is 99.76% and mean error between output value and real value is 2.289℃.

The number of rules of model got by ANFIS are 25, but by proposed fuzzy modeling method is only 5, and the mean error of proposed method is smaller as 2~3 times than ANFIS from simulation experiment result, so that we can know that applying the proposed method is very efficient. Below table shows the comparison of experiment result that we proceed in field by previous result[1] and proposed method.

Table. The comparison of previous result[1] and proposed method

No.	Furnace number	Method	Maximum deviation/℃	Minimum deviation/℃	Mean deviation/℃	Model accuracy/℃
1	No 15	Proposed	4.6	0.1	1.57	99.84
		Previous	4.8	1.1	2.5	88.45
2	No 48	Proposed	6.2	0.8	2.94	99.71
		Previous	7.3	1.6	2.4	83.67
3	No 89	Proposed	11.1	0.4	6.05	99.40
		Previous	8.6	1.9	2.6	82.56

Considering the table, the model accuracy is about 85% and the proposed method is about 99%. That is, though previous method[1] proceed the model updating by interval measurement, the accuracy of model didn't reach at 91%. That cause is that previous research try to get the furnace model, nonlinear object, by only a equation as mentioned over.

Overall, through the simulation experiment by MATLAB and field experiment by matching MATLAB, MYSQL and C++, it was verified practically that the application of the proposed method proceeded successfully.

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