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Predictive fuzzy PID control for temperature model of a heating furnace

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Abstract: In conventional PID scheme, the ensemble control performance may be unsatisfactory due to limited degrees of freedom. Based on such backgrounds, a novel PID control that inherits the advantages of fuzzy PID control and predictive functional control (PFC) is proposed and tested on the temperature model in a heating furnace in this paper. On the basis of the framework of PFC, the fuzzy PID control is introduced to acquire the optimal control law, then an improved PID control strategy is obtained. Finally, the case study on a temperature model of a heating furnace demonstrates the effectiveness of the proposed PID control scheme in comparison with the conventional PID control and the fuzzy self-adaptive PID control.

Keywords: Predictive functional control, fuzzy control, PID control, temperature regulation

1 Introduction

Traditional PID control is widely applied in various industrial processes due to the simple structure and strong adaptability, however, its performance may not be satisfactory due to time-varying and nonlinear effects. Since it is difficult to obtain the precise process model, using the traditional PID control is difficult to further obtain improved control effect [1-2]. Research on PID control has never stopped since it was proposed, and there are many classic tuning methods [3-6]. Zhang et al. proposed a new PID controller through combining predictive functional control (PFC) with conventional PID control and tested the performance on an industrial fractional tower [7]. The temperature of industrial heating furnaces has nonlinear, time lag and time-varying characteristics and control of it is not easy. There are a lot of nonlinear control methods, such as fuzzy control, time delay control (TDC) [8-9], sliding mode control (SMC) [10] and neuron model adaptive PID [11]. Fuzzy control is widely used in nonlinear control, which is based on fuzzy set, fuzzy logic, and fuzzy inference for complex systems [12]. An adaptive system using fuzzy control algorithm can not only make the control system more reliable, but also obtain good control performance [13]. Fuzzy control has strong adaptability and does not require the accurate model of the controlled process. In order to overcome the shortcomings of the traditional PID control, fuzzy control and PID controller can be combined together.

The deficiency of the model/plant mismatch can be compensated for by the prediction error that may occur in the predictive control [14-15]. Based on the output error prediction of a nonlinear system, the time-varying predictive PID controller can solve general predictive PID controller's design in the presence of system restrictions [16]. Through combination of fuzzy control and predictive control, the prediction error is compensated by fuzzy inference [17-19]. The fuzzy control technology combined with the adaptive control and sliding mode control method is applied to the vehicle suspension system to get a better control result, but the control parameters are selected by experience and the optimization of control rules is not realized [20-22].

The purpose of this paper is to develop a novel PID control that inherits the advantages of fuzzy PID control and PFC. Based on prior information, the forecasting model is established as a basic model to predict the process dynamics, and the error between the measured value and predicted value is used as the information to predict the uncertainty. The PID parameters are modified online by using fuzzy inference so that it can meet the requirements under different conditions. The results show that the proposed controller can achieve good dynamic set-point tracking as well as disturbance rejection.

This paper is organized as follows. In section 2, the prediction model is formulated. Then the design of fuzzy PID controller is presented. In section 3, the simulation of heating furnace process is done. Conclusions are drawn in section 4.

2 Predictive Fuzzy PID Control

Predictive fuzzy PID control system mainly consists of prediction and control. The prediction part mainly predicts the temperature of the furnace at the next instants. The control part is completed by the fuzzy PID to let the predicted output track the target value as closely as possible. The structure of predictive fuzzy PID control system is shown in Fig. 1.

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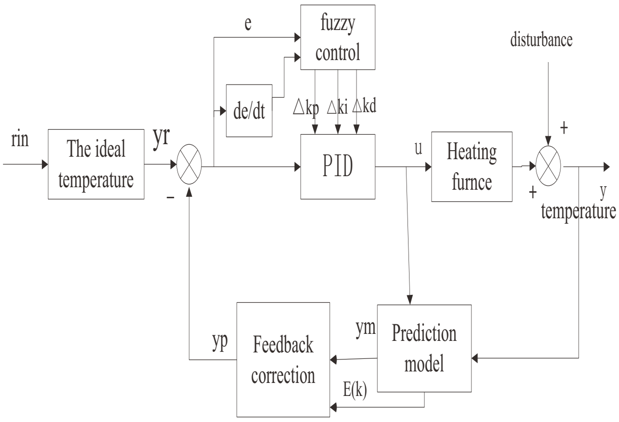


Fig. 1 The structure of fuzzy PID control system.

2.1 Prediction Model

At each time instant k, the *P* step-ahead output prediction should be as close as possible to the given target, namely the ideal curve. In the whole controller design, the PFC idea only plays the role of prediction and does not participate in the system control.

The predictive model of the PFC is a first order model.

$$G(s)=\frac{K_m\,\mathrm{e}^{-\tau_m s}}{T_m s+1} \tag{1}$$

where, τ_m is the time delay and T_m , K_m are the time constant and gain of the process model respectively. After discretization using the zero-order holder, the differenced equation of the model is:

$$y_m(k+1)=a_m y(k)+K_m(1-a_m)u(k-L) \tag{2}$$

where, $a_m=e^{(-T_s/T_m)}$, T_S is the sample time, *L* is τ_m/T_s integral part.

Unlike predictive control, PFC requires that control performance be related to the structure of the control input. In the PFC, the new control function is expressed as a linear combination of some known basis functions, and the basis function can be a step function, a slope function and so on. In this paper, we select a step function as the basis function. According to the step function, we can obtain [23]:

$$u(k+i)=u(k),\ i=1,2,\cdots \tag{3}$$

According to PFC, the predicted output value of the process in time domain is derived according to the current information and the control action in the future. Therefore, let $L=0$ and then we can predict the future P step output value of the model as follows:

$$y_m(k+P)=a_m^P y_m(k)+K_m(1-a_m^P)u(k) \tag{4}$$

where, $a_m^P y_m(k)$ is the free response of the model, $K_m(1-a_m^P)u(k)$ is the forced response of the model.

To eliminate the effect of disturbance and model/plant mismatch, we can use the feedback correction to the predicted value obtained by (4) as follows:

$$e(k)=y_r(k)-y_p(k) \tag{5}$$

$$y_p(k)=y_m(k+P)+y(k)-y_m(k) \tag{6}$$

$$y_r(k+i)=c(k+i)-\lambda^i[c(k)-y(k)] \tag{7}$$

where, y_p is corrected predicted value, $y_m(k+i,k)$ is the model output values of the *k*+1 time instant, y_r is reference trajectory, *c* is set-point, λ is the smoothing factor with $\lambda=\exp(-T_s/T_r)$, $0<\lambda<1$, T_S is the sampling time, T_r is the expected closed loop response time, $y(k)$ is the actual process output at time instant *k*.

When $L\neq 0$ and based on Smith predictor, PFC still uses the model with $L=0$, but the system output needs to be modified as follows:

$$y_{pav}(k)=y_p(k)+y_m(k)-y_m(k-L) \tag{8}$$

where, $y_{pav}(k)$ is the revised process output value, and the revised forecast error is

$$E(k)=y_{pav}(k)-y_m(k) \tag{9}$$

2.2 The Fuzzy PID Control

Fuzzy control does not depend on the controlled model and uses linguistic variables to describe the system characteristics rather than numerical variables, i.e., it is based on the system dynamic information and fuzzy rules inference to get the appropriate control, however, the control precision is not ideal. Based on this fact, the good dynamic tracking ability of fuzzy control and the good stability of PID are combined.

The design of a two-input three-output fuzzy controller with the error *E* and the rate of change *EC* as inputs is as follows:

$$\begin{cases} K'_p=K_p+\Delta k_p \\ K'_i=K_i+\Delta k_i \\ K'_d=K_d+\Delta k_d \end{cases} \tag{10}$$

Where, K_p , K_i , K_d are Fuzzy PID parameters, K'_p , K'_i , K'_d are the revised fuzzy PID parameters, Δk_p , Δk_i , Δk_d are parameters to be determined. The control structure is shown in Fig. 1.

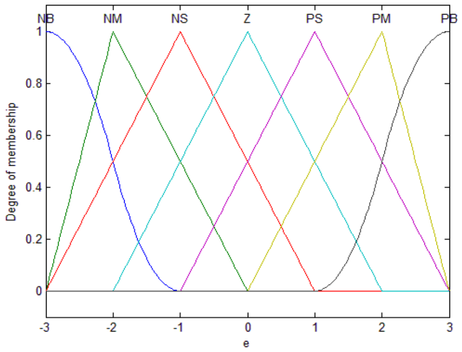
2.3 Design of Fuzzy PID Controller for Prediction

(a) The Domain and Language Variable Settings

The two-input three-output fuzzy controller is used to adjust the PID parameters. The input fuzzy variable error *E*, error change rate of *EC* and output fuzzy variables ΔK_p , ΔK_i , ΔK_d were selected as [-3 3], [-3 3], [-0.3 0.3], [-0.06 0.06], [-3 3], and the fuzzy language set is [*NB NM NS ZO PS PM PB*].

(b) Membership Function Settings

Different shapes of the membership function will cause different influence on control performance. When choosing a membership function of fuzzy variables, low-resolution fuzzy sets will be adopted for bigger error and high-resolution fuzzy sets for the error close to zero. Here Triangular membership functions and sigmoid membership functions are adopted for the input linguistic variables and output linguistic variables. The membership functions for the input E, EC and the output $\Delta k_p, \Delta k_i, \Delta k_d$ are used as follows.



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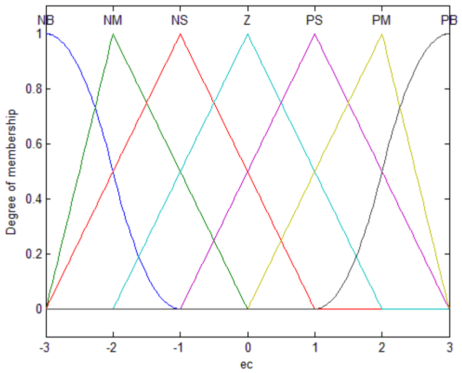

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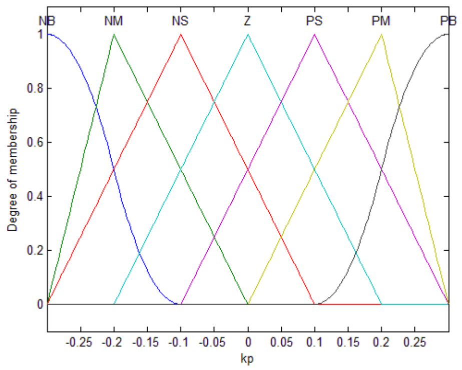

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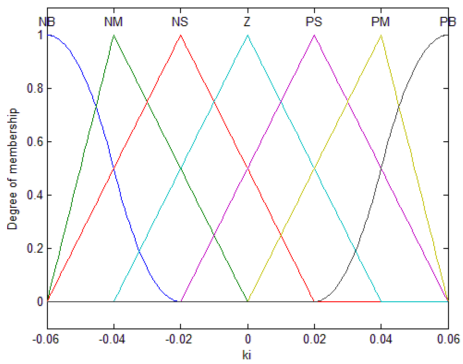

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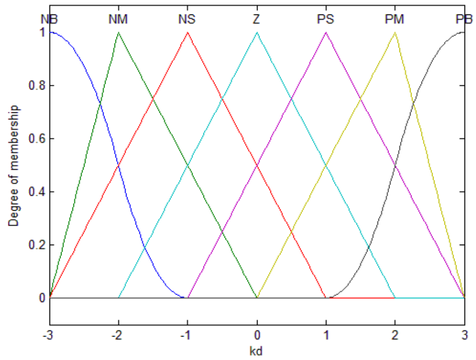


(e)

Fig. 2 Membership functions.

(c) Control Rules Set

The fuzzy control is to summarize technical knowledge and practical experience of engineering design, then establish a proper table of fuzzy rules. To design the two-input three-output fuzzy PID controller, the control rules are shown in Table 1 [24].

Table 1 Fuzzy Rule Table

e \ Δk_p \ ec	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	*PB*	*PB*	*PM*	*PM*	*PS*	*ZO*	*ZO*
NM	*PB*	*PB*	*PM*	*PS*	*PS*	*ZO*	*NS*
NS	*PM*	*PM*	*PM*	*PS*	*ZO*	*NS*	*NS*
ZO	*PM*	*PM*	*PS*	*ZO*	*NS*	*NM*	*NM*
PS	*PS*	*PS*	*ZO*	*NS*	*NS*	*NM*	*NM*
PM	*PS*	*ZO*	*NS*	*NM*	*NM*	*NM*	*NB*
PB	*ZO*	*ZO*	*NM*	*NM*	*NM*	*NB*	*NB*

(a)

e \ Δk_i \ ec	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	*NB*	*NB*	*NM*	*NM*	*NS*	*ZO*	*ZO*
NM	*NB*	*NB*	*NM*	*NS*	*NS*	*ZO*	*ZO*
NS	*NB*	*NM*	*NS*	*NS*	*ZO*	*PS*	*PS*
ZO	*NM*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PM*
PS	*NM*	*NS*	*ZO*	*PS*	*PS*	*PM*	*PB*
PM	*ZO*	*ZO*	*PS*	*PS*	*PM*	*PB*	*PB*
PB	*ZO*	*ZO*	*PS*	*PM*	*PM*	*PB*	*PB*

(b)

e \ Δk_d \ ec	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	*PS*	*NS*	*NB*	*NB*	*NB*	*NM*	*PS*
NM	*PS*	*NS*	*NB*	*NM*	*NM*	*NS*	*ZO*
NS	*ZO*	*NS*	*NM*	*NM*	*NS*	*NS*	*ZO*
ZO	*ZO*	*NS*	*NS*	*NS*	*NS*	*NS*	*ZO*
PS	*ZO*	*ZO*	*ZO*	*ZO*	*ZO*	*ZO*	*ZO*
PM	*PB*	*NS*	*PS*	*PS*	*PS*	*PS*	*PB*
PB	*PB*	*PM*	*PM*	*PM*	*PS*	*PS*	*PB*

(c)

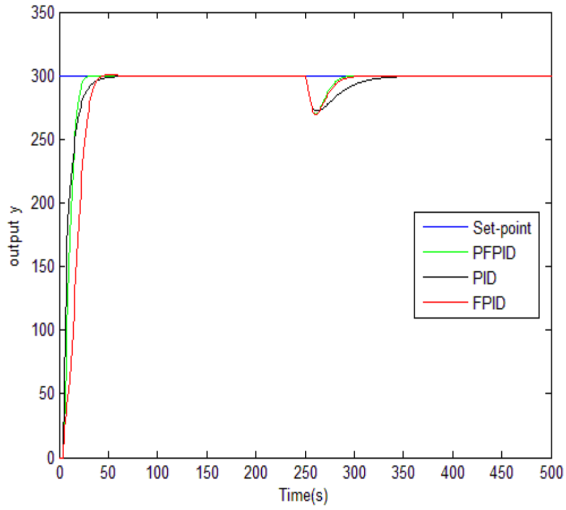
3 Case Study

A heating furnace model is adopted here as follows.

$$G(s) = \frac{e^{-100s}}{600s+1} \quad (11)$$

In the fuzzy PID control, the fuzzy domains for $E, EC, \Delta K_p, \Delta K_i, \Delta K_d$ were selected as [-3 3], [-3 3], [-0.3 0.3], [-0.06 0.06], [-3 3], respectively; the quantitative factors were selected as $k_e = 0.001, k_{ec} = 0.001$, and the proportion factors were selected as $k_p = 0.001$, $k_i = 0.008$, $k_d = 12.8$. Here $T_s = 30$, $P = 9$ and the PID parameters are obtained by the internal model tuning method as $K_p = 2.1667$, $K_i = 0.0033$,$K_d = 100$. The set-point is 300 and the output disturbance with amplitude of -5 is added to the process.

Here the PID control, fuzzy PID (FPID) and predictive fuzzy PID (PFPID) are compared and simulation results are shown in Fig.4 and Table 2.



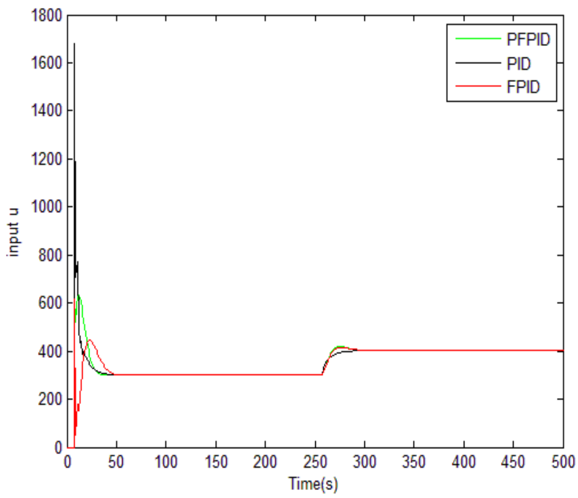


Fig. 4 Closed-loop response with disturbance.

As can be seen from Fig.4, smaller overshoots, oscillations and fluctuations of the output responses of the PFPID controller are obtained. The response time of PFPID control system is fast, disturbance can be quickly rejected and the overshoot and oscillation are relatively small. It shows that the overall control performance is improved compared with PID and fuzzy PID control system.

Table 2 Response Index Of Control

Controller	Response-time	Overshoot	Disturbance rejection time
PID	35	27.8	57
PID	33	30.4	33
PFPID	22	30.4	30

4 Conclusion

A new predictive fuzzy PID controller is proposed that combines FPID controller and predictive control. The fuzzy rule and PFC based PID design is proposed and simulation results show that the controller can track the target more effectively than fuzzy PID and traditional PID. By comparison, PFPID control has less overshoot and short rise time compared with FPID control and PID control.

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