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Automation

A complex control system based on the fuzzy PID control and state predictor feedback control

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Abstract: A multi-mode adaptive controller was proposed. The controller features in the combination of Bang-bang and Fuzzy PID controls with state predictor. When large error exists, the controller operates in Bang-bang mode, otherwise it works as a fuzzy PID controller. For only few parameters to be adjusted, the real time controlled system achieveed good stability and fast response. Furthermore, the introduction of state observer was also discussed to extend the capability of the proposed controller to the plant with time-delay factors. The classical PID controller and the multi-mode controller were applied to the same second-order system successively. By comparison of the simulation results, the effectiveness of the controller were shown. At last, on electric-wire production line, this approach was practiced to control electric-wire diameter with an additive random disturbance signal. The test result further proved the effectiveness of the multi-mode controller.

Key words: multi-mode; fuzzy PID; state predictor; time delay

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1 Introduction

The PID controller is one of the most commonly used controllers in the industrial closed loop control system for its simple algorithm, good robustness and stability. However, it can not simultaneously meet the requirement of fast and stable performance of some systems containing Time Delay.

Nowadays, many kinds of intelligent PID control methods, such as Expert PID, Fuzzy PID, the genetic algorithmetic PID and the neural net PID are applied to deal with this problem. However, these methods can hardly be applied to real time plant, due to the calculation speed limitations of the controller.

In this paper, a two-inputs (the error and its derivative) Fuzzy PID controller was proposed, which can adjust its parameters automatically according to the system's error and differential error. For only three parameters to be adjusted, it is more suitable to control real time plant than other controllers. Meanwhile, in order to improve the poor control quality, an optimal predictor feedback control method for controlling the system with time delay was also proposed, which can identify the state and the parameters of the system and obtain the optimal predicating feedback $y^*(k+d)$ by the Recursive LSM (Least Square Method).

2 Design of fuzzy PID controller

The structure of the system is shown in **figure 1**.

When the error $e(k)$ is large, the system works in Bang-bang control mode. The control switch turns down and the PID gains are set to the initial values derived from the identification. When the output signal falls into the error dead-zone, the switch turns up to connect the self-tuning Fuzzy PID controller into the loop.

The switch action is determined by the following rule.

If the error dead-zone is $|e|\geqslant\alpha^*\gamma$, then bang-bang control else is Fuzzy PID control. Where γ is a preset value, the value α ($0<\alpha<1$) should be selected to guarantee that in Bang-bang control mode, the system can offer enough information for identification.

The model of a classical PID controller can be described as a linear difference equation:

$$u(k)=u(k-1)+k_{\mathrm{p}}[e(k)-e(k-1)]+k_{\mathrm{i}}e(k)+$$

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$$k_d[e(k)-2e(k-1)+e(k-2)] \tag{1}$$

where T, k_p, k_i, k_d are the sampling period, proportional, integral and derivative gains respectively.

Suppose $k_p \in [k_{p,min}, k_{p,max}]$ and $k_d \in [k_{d,min}, k_{d,max}]$.

Then the linear transformation and normalization can be applied that

$$k_p' = (k_p - k_{p,min})/(k_{p,max} - k_{p,min}) \tag{2}$$

$$k_d' = (k_d - k_{d,min})/(k_{d,max} - k_{d,min}) \tag{3}$$

clearly, $k_p' \in [0,1]$; $k_d' \in [0,1]$, the integral gain is:

$$k_i = k_p/(\alpha T_d) = k_p^2/(\alpha k_d) \tag{4}$$

The parameters k_p', k_d' and α are determined by the fuzzy rules according to the error $e(k)$ and its first order difference $\Delta e(k)$. The MFs (Membership Function) for $e(k)$and $\Delta e(k)$ are shown in **figure 2**. For the $e(k)$ and $\Delta e(k)$, seven labels from NL(negative large) to PL(positive large) are located on their universe of discourse.

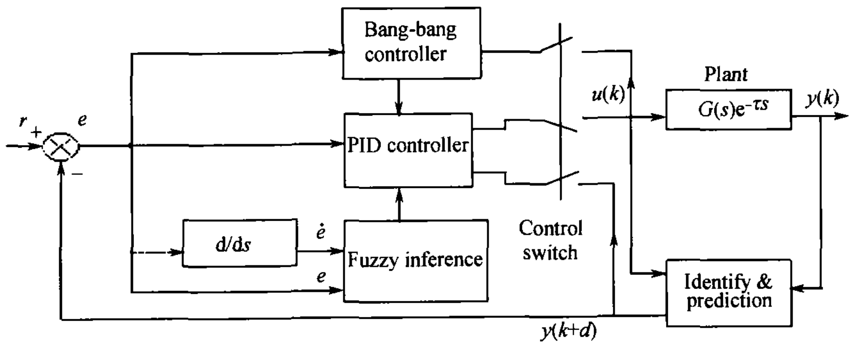

Figure 1 The structure of system.

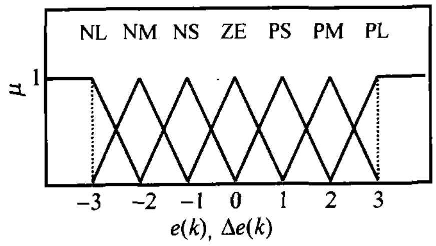

Figure 2 Membership function for $e(k)$ and $\Delta e(k)$.

The MFs for k_p', k_d' can be described as follows (shown in **figure 3**):

For SMALL k_p', k_d':

$$\mu_s(x) = \frac{1}{4}\ln x \text{ or } x_s(\mu) = e^{-4\mu} \tag{5}$$

For LARGE k_p', k_d':

$$\mu_B(x) = \frac{1}{4}\ln(1-x) \text{ or } x_B(\mu) = 1 - e^{-4\mu} \tag{6}$$

while the MF for α is defined as in **figure 4**.

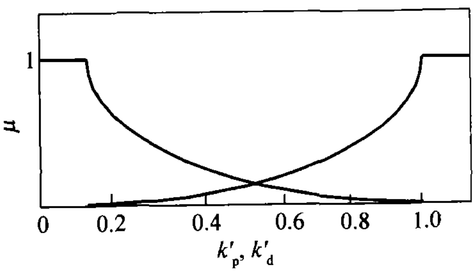

Figure 3 MF for k_p' or k_d'.

After the defuzzification of k_p', k_d' and α, parameters of PID can be calculated by the equations (2), (3) and (4).

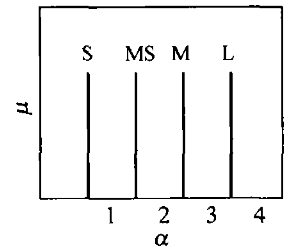

Figure 4 MF for α.

3 The optimal predictor design

The plant $G_p(s)e^{-\tau s}$ can be generally described by the difference equation:

$$y(k) = \frac{z^{-d}B(z^{-1})}{A(z^{-1})}u(k) + \lambda\frac{C(z^{-1})}{A(z^{-1})}\varepsilon(k) \tag{7}$$

The $C(z^{-1})/A(z^{-1})$ can be decomposed into the Diophantine equation:

$$\frac{C(z^{-1})}{A(z^{-1})} = F(z^{-1}) + z^{-d}\frac{G(z^{-1})}{A(z^{-1})} \tag{8}$$

The performance index of the d-step-ahead prediction $y^*(k+d)$ with the least prediction variance is defined as:

$$J = E\left[\frac{F(z^{-1})B(z^{-1})}{C(z^{-1})}u(k) + \frac{G(z^{-1})}{C(z^{-1})}y(k) - \hat{y}(k+d\mid k)\right]^2 + E[\lambda F(z^{-1})\varepsilon(k+d)]^2 \tag{9}$$

To get the minimum J, the following equation should be satisfied to get the optimal prediction of $y(k+d)$ at time k:

$$\hat{y}^*(k+d\,|\,k)=\frac{G(z^{-1})}{C(z^{-1})}y(k)+\frac{F(z^{-1})B\ (z^{-1})}{C(z^{-1})}u(k) \tag{10}$$

The output of the optimal predictive PID control system

$$y(k)=\frac{z^{-d}B(z^{-1})P(z^{-1})}{R(z^{-1})A(z^{-1})+B(z^{-1})P(z^{-1})}R_{\text{ref}}+\frac{P(z^{-1})F(z^{-1})B(z^{-1})+R(z^{-1})C(z^{-1})}{R(z^{-1})A(z^{-1})+B(z^{-1})P(z^{-1})}\varepsilon(k) \tag{11}$$

where R_{ref} is the reference input, $P(z^{-1})=p_0+p_1z^{-1}+p_2z^{-2}$; $R(z^{-1})=1-z^{-1}$.

From equation (11), it can be clearly seen that the optimal predictive system doesn't have time-delay factor in its characteristic polynomial.

4 Experimental results

Firstly, identify the d, A and B in following equation with simplified GLS (Generalized Least Square) method, and then identify the disturbance with the simplified recursion algorithm.

Rewriting equation (7) in modified GLS form,

$$A(z^{-1})y(k)=B^*(z^{-1})u(k) \tag{12}$$

Where $B^*(z^{-1})=b^*z^{-1}+\cdots+b^*_{n+d\max}z^{-(n+d\max)}$.

$d_{\max}$ is the upper limit of time-delay, which is estimated in advance and satisfies $0\leqslant d\leqslant d_{\max}-1$, also have the following equations:

$b_i^*=0$ $(i=1, \cdots, d, n+1+d, \cdots, n+d_{\max})$,

$b_j^*=b_{j-d}$ $(j=d+1, \cdots, d+n)$.

To estimate the parameters of the model of equation (12) with RLS (Recursive Least Square), assume:

$\hat{\theta}=(\hat{a}_1, \cdots, \hat{a}_n;\ \hat{b}_1, \cdots, \hat{b}_{n+\max})^{\mathrm{T}}$,

$X=[-y(k-1), \cdots, -y(k-n); u(k-1), \cdots, u(k-n-d_{\max})]$.

when $k\to\infty$, $\hat{b}^*_i\to 0$; with the identified coefficient of $\hat{B}^*(z^{-1})$, the error function is obtained:

$$F(d)=[\hat{B}^*(1)-\hat{B}^*_d(1)],$$

where

$$\hat{B}^*(1)=\sum_{i=1}^{n}\hat{b}_i^*(i=1,\ldots,n+d_{\max});$$

$$\hat{B}^*_d(1)=\sum_{i=1}^{n}b^*_{i+d}(d=0,\ldots,d_{\max}-1).$$

When $F(d)$ is minimum, the corresponding d is the number of delayed steps.

When d, B and A are obtained, the disturbance can be directly estimated by the following equation:

$$\varepsilon^*(k)=\lambda C(z^{-1})\varepsilon(k)=A(z^{-1})y(k)-z^{-d}B(z^{-1})u(k) \tag{13}$$

The model for simulation is drawn from a practical wire production line. The process can be modeled as a difference equation:

$$y(k)=-a_1y(k-1)-a_2y(k-2)+u(k-1)+b_1u(k-2)+b_2u(k)+\varepsilon(k)+c_1\varepsilon(k-1)$$

Its corresponding continuous model is:

$$G(s)=\frac{\mathrm{e}^{-\tau s}}{S^2+aS+b}$$

The schematic diagram of the diameter-control part in electric wire production is shown in **figure 5**. The simulation results with different process parameters are shown in **figures 6**, and moreover, the dynamic response is shown in **figure 7**.

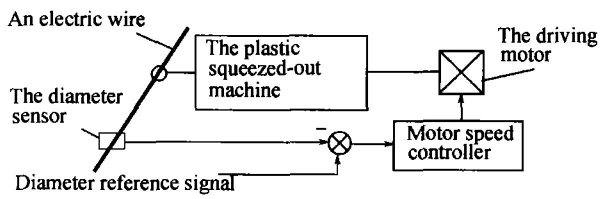

Figure 5 The diameter-control part.

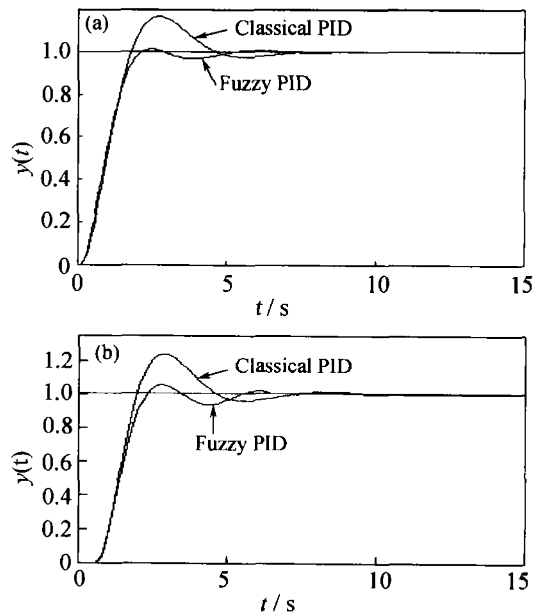

Figure 6 Step-response indicators, (a) a=2.25, b=3, τ=0.1; (b) a=2, b=3, τ=0.6.

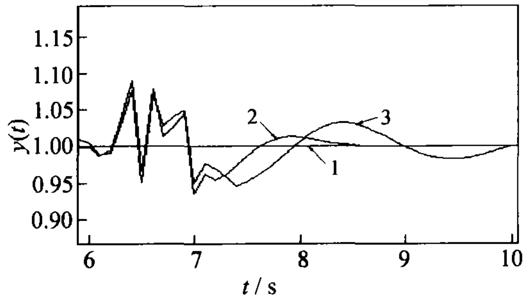

Figure 7 Transient-response indicators a=2, b=3, τ=1.1. 1—the squeezing speed of the plastic squeezed-out machine; 2—the system's actual wire diameter with a fuzzy PID controller with the same disturbance signal; 3—the system's actual wire diameter with a classical PID with the same disturbance signal.

5 Conclusions

In comparison with the classical PID controller, the multi-mode adaptive controller can achieve better dynamic and static performance. And to a certain degree, the adoption of predicator eliminates the influence of varying parameters, such as the time delay factor τ in the plant.

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