Research on Fuzzy I-PD Preview Control for Nonlinear System*

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In this paper, we propose a new approach on nonlinear preview control with fuzzy logic. Because preview control can decrease not only the overshoot but also the control energy, there have been many approaches on preview control. However, as these approaches are based on linearized models⁽¹⁸⁾, they cannot get a good result when they are applied to nonlinear plants. So we propose a fuzzy preview control to compensate the nonlinear properties of plant. Here, first, a simple Fuzzy Logic Control (S-FLC) with single-input-single-output is introduced. This kind of Fuzzy Logic Control can decrease the number of rules and make the fuzzy reasoning be more quickly. Second, using the I-PD control system proposed by T. Kitamori, fuzzy I-PD control's scaling factors are designed with matching technique. Then to compensate nonlinear properties of plant, two parameters are injected and optimized with Genetic Algorithm (GA). Third, a new designing scheme of preview control element using fuzzy theory is proposed and the preview control element is optimized with GA under a performance criteria. Being designed on the nonlinear model, it will make the fuzzy preview control be more suitable to nonlinear plant. At last, some experiments with a two-cascaded tank system illustrate the efficiency of the proposed approach.

Key Words : Fuzzy Set Theory, I-PD Control, Genetic Algorithm, Preview Control, Optimal Control, Nonlinear Control, Process Control, Digital Control

1. Introduction

Fuzzy Logic Control (FLC) has emerged as one of the most active areas in the application of fuzzy set theory since Mamdani's application to automatic control area. It may be true that some control engineers, who would try to adopt the fuzzy set theory to system control, focus on researches^{(5)-(8),(14),(15)} how to design the rule base according to experts knowledge and the scaling factors. However, in spite of many practical successes, till now, the approach of simplistic FLC is experience-oriented⁽¹⁶⁾. On the other hand, since fuzzy systems implement static nonlinear input-output mappings, many successful researches and applications on fuzzy nonlinear control have been published.

In many control systems, reference input can be

previously known, for example, step or ramp. If these kinds of future message can be applied as preview control, it should make system's response more rapid and less overshoot. In Ref.(4), an optimal preview servo system constructed with state feedback is given. But, in industry, especially in process control, PID (including some control method like PID) is also widely used since it is simple and easy to be designed. However, PID is not suitable to be used for preview control because it already has feedforward action to reference input. So, I-PD control was used as the feedback controller for preview control system. Therefore, we proposed an I-PD preview control system⁽¹⁸⁾ with simpler control law designed on partial model matching techniques⁽¹⁾. One of the advantages of this approach is that it has the similar properties to the optimal preview servo system just with output feedback control.

However, to nonlinear plant, when a plant has stronger nonlinear property, the improvement of the control performance by means of some linear controller designed on an approximate linear model has a limit. To overcome this, we consider that if the controller has nonlinear property and compensates the

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nonlinear property of the plant, the control performance could be more improved.

In this paper, we propose a design method of preview control for nonlinear plant, named Fuzzy I-PD Preview Control (FIPC). The FIPC consists of two parts. First one is the feedback control named Fuzzy I-PD Control (FIC). To design it, we adopt an approach combining the I-PD control and Fuzzy Control. Through this approach we can design the scaling factors of the FIC by matching with I-PD's parameters. Moreover, to let the FIC be able to compensate the nonlinear properties of plant, two parameters named k_σ and k_c are introduced. Both of them are designed with Genetic Algorithm (GA). Second one is the fuzzy preview control. The preview control with FLC will also be optimized with GA based on the nonlinear plant. It may be also expected to compensate the nonlinear properties of plant.

GA is general-purpose optimization algorithm⁽¹³⁾ based on Darwinian Survival-of-the-fitness theory. Numerous works⁽⁹⁾⁻⁽¹²⁾ have been done in the applications of GA to design and implement fuzzy systems. Generally, one of disadvantages of search algorithms is in random search. In this paper, the FIC is first designed by matching with the I-PD control system and is next adjusted with GA to be suitable to nonlinear plant. Because the I-PD control system has around an optimal result for linearized plant, the searching area of GA is not random. GA is also used to design the fuzzy preview control element. Since preview control is feed forward one, it has nothing to do with the system's stability.

The composition of this paper is as follows. In section 2, we will show the structure of Fuzzy I-PD Preview Control (FIPC) system. In section 3, the feedback control system is designed, where in subsection 3.1 we will introduce the Simple Fuzzy Logic Control (S-FLC), in subsection 3.2 I-PD control and its design method will be introduced briefly, in subsection 3.3 how to design the FIC matching with the I-PD control is discussed, and in subsection 3.4 two parameters are injected into the FIC to improve the nonlinear property. In section 4, preview control element designed with GA will be introduced. In section 5, the practical applicability of the proposed algorithm is examined through the experiments with two-cascaded tanks system. Section 6 concludes this paper.

Acronyms:

- FLC: Fuzzy Logic Control.
- FIC: Fuzzy I-PD Control
- FIPC: Fuzzy I-PD Preview Control
- GA: Genetic Algorithm
- S-FLC: Simple Fuzzy Logic Control
- MF: Membership Function

2. Structure of Fuzzy I-PD Preview Control (FIPC) System

Figure 1 shows the structure of the FIPC system. This system is divided into two portions, feedback and preview control, and design approach of each portion will be proposed in sections 3 and 4, respectively. In Fig. 1, *DS* means distance-calculating element to translate multi-input FLC into single-input FLC. *S-FLC* means a simple general FLC. *Preview* is how to use the future message. And *FLC-P* means FLC for preview control, whose output produces a preview control difference input $\Delta u_p(k)$.

3. Design of Fuzzy I-PD Control (FIC)

3.1 Simple Fuzzy Logic Control (S-FLC)

In this section, a simple fuzzy logic control with single-input-single-output will be discussed.

Notice the rule base of two-dimensional FLC in Fig. 2. The fuzzy number on diagonal line is ZO. This means, if the e and Δe have the same fuzzy linguistic variable and opposite sign, the output fuzzy linguistic variable is ZO. And also, some parallel lines of diagonal divide the rule base into the same fuzzy linguistic variable areas. Figure 3 shows that if the distance from a point to diagonal line is known, the FLC's output fuzzy linguistic variable can be gotten and the distance is given by Eq. (1).

Fig. 1 Fuzzy I-PD Preview Control System

$e \Delta e$	NB	NS	ZO	PS	PB
PB	ZO	NS	NM	NB	NB
PS	PS	ZO	NS	NM	NB
ZO	PM	PS	ZO	NS	NM
NS	PB	PM	PS	ZO	NS
NB	PB	PB	PM	PS	ZO

Fig. 2 Rule base of FLC

$$DS = \frac{e + \lambda_1 \Delta e}{\sqrt{1 + \lambda_1^2}} \quad (1)$$

For a more general case of FLC with n -dimensional, let's suppose $E^T = \{e, \Delta e, \dots, \Delta^{n-2}e, \Delta^{n-1}e\}^T$ and $\lambda = \{\lambda_1, \dots, \lambda_{n-2}, \lambda_{n-1}\}$, the distance to ZO plane (n -dimensional hyperplane) will be given by

$$DS = \frac{\lambda E}{\|\lambda\|} \quad (2)$$

where $\|\lambda\|$ is the norm of λ . Therefore, according to the distance from a point to diagonal line, the output fuzzy linguistic variable can be decided easily. Thus, n -dimensional FLC can be transferred to one-dimensional one.

3.2 I-PD control

I-PD control, which was proposed by T. Kitamori⁽¹⁾ and its extended research^{(2),(17)}, enables one to design control systems in situation that the dynamic characteristics of plants are not known perfectly. The structure of sampled data I-PD control system is shown in Fig. 4. The transfer function of plant in continuous-time can be described as

$$G_p(s) = \frac{b}{a} = \frac{b_0 + b_1s + b_2s^2 + \dots}{a_0 + a_1s + a_2s^2 + \dots} = \frac{1}{\frac{a}{b}} = \frac{1}{a_0 + a_1s + a_2s^2 + \dots} \quad (3)$$

And a reference model of the I-PD control system is given in

$$G_m(s) = \frac{1}{a_0 + a_1s + a_2(\sigma s)^2 + \dots} \quad (4)$$

where σ means the impulse response's center of gravity of reference model. If σ becomes big, dynamic

Fig. 3 Distance of S-FLC

Fig. 4 Sampled-Data I-PD Control System

response of the reference model becomes slow. Various reference models can be used to design the I-PD control system⁽³⁾, such as Binomial-ITAE minimum model, Butterworth model, etc.

In Ref. (1), the parameters of I-PD controller in difference operator, k^* , f_0^* and f_1^* , are designed, so that the transfer function of the control system coincides with $G_m(s)$ which has the smallest value of σ from lower frequency components. Then the control parameters in Fig. 4 yield

$$\tilde{k}^* = \tau k^*; \quad \tilde{f}_1^* = -f_1^* \frac{1}{\tau}; \quad \tilde{f}_0^* = f_1^* \frac{1}{\tau} + f_0^* \quad (5)$$

According to these steps, the I-PD control law can be described as

$$u_b(k) = \tilde{k}^* \sum_{i=0}^k e(i) - \tilde{f}_0^* y(k) - \tilde{f}_1^* y(k-1) \quad (6)$$

and its incremental form is

$$\Delta u_b(k) = \tilde{k}^* e(k) - \tilde{f}_0^* y(k) + (\tilde{f}_0^* - \tilde{f}_1^*) \times y(k-1) + \tilde{f}_1^* y(k-2) \quad (7)$$

3.3 Fuzzy I-PD Control (FIC) and its design approach

In this section, the structure of FIC system and its design method through matching it with I-PD control system are proposed.

If the MFs for both antecedent and consequent are uniform, the input and output of S-FLC have approximately linear relationship. In FIC, using the rule base of the S-FLC, we should design four parameters including scaling factors s_1 , s_2 , s_3 and output gain k_f . As described above, the relation between DS and Δu_f is shown in

$$\Delta u_f(k) = -DS(k) \quad (8)$$

where

$$DS(k) = \frac{Fe(k) + \lambda_1 \Delta Fy(k) + \lambda_2 \Delta^2 Fy(k)}{\|\lambda\|} \quad (9)$$

$$Fe(k) = s_1 e(k);$$

$$\Delta Fy(k) = s_2 \Delta y(k) \quad \Delta^2 Fy(k) = s_3 \Delta^2 y(k) \quad (10)$$

and where $\Delta y(k) = y(k) - y(k-1)$ and $\Delta^2 y(k) = y(k) - 2y(k-1) + y(k-2)$.

Substituting Eq. (9) and Eq. (10) into Eq. (8), we get

$$\Delta u_f(k) = -\frac{1}{\|\lambda\|} k_f [s_1 e(k) + (\lambda_1 s_2 + \lambda_2 s_3) y(k) - (\lambda_1 s_2 + 2\lambda_2 s_3) y(k-1) + \lambda_2 s_3 y(k-2)] \quad (11)$$

Comparing Eq. (11) with Eq. (7), let their parameters match with each other, then we can obtain the following equations.

$$-\frac{1}{\|\lambda\|} k_f \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda_1 & \lambda_2 \\ 0 & -\lambda_1 & -2\lambda_2 \\ 0 & 0 & \lambda_2 \end{bmatrix}}_A \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \tilde{k}^* \\ -\tilde{f}_0^* \\ \tilde{f}_0^* - \tilde{f}_1^* \\ \tilde{f}_1^* \end{bmatrix} \quad (12)$$

If we assume that

$$s_1 = \frac{1}{R} \quad (13)$$

where R is the considered maximum amplitude of reference inputs. So we can solve the rest equations as

$$k_f = -\|\lambda\| R \tilde{k}^*, \quad s_2 = -\frac{\tilde{f}_0^* + \tilde{f}_1^*}{\lambda_1 R \tilde{k}^*}, \quad s_3 = \frac{\tilde{f}_1^*}{\lambda_2 R \tilde{k}^*} \quad (14)$$

Here, the vector λ can be decided by fuzzy universe of Fe , ΔFy and $\Delta^2 Fy$. If all of the fuzzy universe are $[-1, 1]$, the $\lambda = \{1, \lambda_1, \lambda_2\}$ is unit vector.

Actually, substituting Eqs.(13) and (14) into Eq.(11), we see that R is nothing to do with the $\Delta u_f(k)$. We select the R as the maximum amplitude of reference inputs, just because the S-FLC has saturation when the input is out fuzzy universe.

However, since the I-PD control is linear one, FIC matching with the I-PD control will lose its nonlinear property. The next section discusses how to compensate nonlinear properties of plant with FIC.

3.4 Improving nonlinear property of Fuzzy I-PD Control (FIC)

Two kinds of MFs are shown in Fig. 5 and they are named as Membership Functions of Uniform (MFU) and Membership Functions of Zero strain (MFZ). The fuzzy decision and defuzzification use Madmdani model. When MFU is used for antecedent, the control surfaces of MFU and MFZ for consequent are shown in Fig. 6.

We see that if MFs for both antecedent and consequent are uniform its nonlinear property is weak. To enforce the nonlinear property, the un-uniform MFs such as MFZ for consequent are considered here. However, the gain of MFZ becomes smaller than that of MFU, so two parameters named k_c and k_σ are injected into FIC and the best pair are searched by GA.

The output gain k_f of FIC is tuned by

$$k_f' = k_c k_f \quad (15)$$

It will change the fuzzy control surface as shown in

Fig. 5 Membership Function of S-FLC, (a) Membership functions of uniform (MFU), (b) Membership functions of zero strain (MFZ)

Fig. 6, and if $k_c > 1$, the fuzzy output becomes bigger, and will cause the response faster, and it also can enforce the nonlinear property of fuzzy control. But only changing the output's gain with k_c will cause a big overshoot and under damping. Here, the other parameter named k_σ is used to adjust as

$$\sigma' = k_\sigma \sigma \quad (16)$$

It can change the dynamic response of the I-PD control system, e.g., $k_\sigma > 1$ will cause the response become slow with longer rise time and less overshoot. k_σ and k_c have opposite effectiveness to the system, and a good pair of them searched by GA can let the FIC be more suitable to the nonlinear plant.

Before using GA, the parameters must be coded to binary bit strings. The strings are shown as

$$\underbrace{k_\sigma}_{10 \dots 0 \quad n} \quad \underbrace{k_c}_{01 \dots 1 \quad m} \quad (17)$$

where n and m is the length of strings for k_σ and k_c . So, k_c and k_σ can be transferred to real data as:

$$k_\sigma = k_{\sigma 1} + f_\sigma \frac{b_\sigma}{2^n - 1} \quad (18)$$

$$k_c = k_{c1} + f_c \frac{b_c}{2^m - 1} \quad (19)$$

where b_σ is $[0, 2^n - 1]$ and b_c is $[0, 2^m - 1]$, and f_σ and f_c are gains. The range of k_c and k_σ are $[k_{\sigma 1}, k_{\sigma 1} + f_\sigma]$ and $[k_{c1}, k_{c1} + f_c]$ respectively. To improve the precision, the strings should be long enough.

Here, the performance criteria is defined as

$$J = \sum_{k=1}^K \{e^2(k) + \rho \Delta u^2(k)\} + \gamma Ov \quad (20)$$

where $e(k)$ is error, $\Delta u(k)$ is increment of control input, Ov is overshoot, and ρ and γ are weights. One part of Eq.(20) is quadratic form performance criteria, the other part is related to overshoot. In many references, the overshoot is designed for about 10% since the process control systems have not always focused on damping characteristics. But here, we want to design a system holding small overshoot and

Fig. 6 Fuzzy control surface tuned by k_c

good quick response. So, the last term of Eq. (20) is used to limit the overshoot. With computer simulation, the responses of the control system can be obtained. Then J can be calculated with these responses.

Design of feedback control system is complete when a better pair of k_σ and k_c are obtained with GA. Then the fuzzy preview control element is designed also with GA in next step.

4. Design of Fuzzy Preview Control with GA

Preview control element is designed to make the steady state velocity error to ramp reference input as small as possible, and it can also decrease the control energy and improve the response.

Note the feed forward portion in Fig. 1, *Preview* is how to use the future message and $\Delta r_p(k)$ is defined as

$$\Delta r_p(k) = \frac{\sum_{i=1}^{L_p} w_i [r(k+i) - r(k)]}{\sum_{i=1}^{L_p} w_i} \quad (21)$$

where w_i is the weight. Choosing Gaussian function, it is defined as

$$w_i = e^{-\frac{(i-1)^2}{2\sigma^2}} \quad (22)$$

Equations (21) and (22) mean that the farther the future message (reference input) is, the weaker it works to preview control action in current time. *FLC-P* means FLC for preview control, whose output produces a preview control incremental input $\Delta u_p(t)$. Next, how to design the preview control element with GA is discussed.

Here, we consider MFs for both antecedent and consequent are triangular. Because FLC of integral type is used for preview control element's design, the *FLC-P* must ensure that $\Delta u_p(k) = 0$ when $\Delta r_p(k) = 0$. To do this, the simplest method is to let MFs for antecedent and consequent be symmetrical. Based on this, only half of MFs should be designed by GA. If we define the linguistic variables for both antecedent and consequent as $A_{i\pm}$ and $C_{i\pm}$, the rule base is defined as

- (1) : if $\Delta r_p(k)$ is A_{N-} then $\Delta u_p(k)$ is C_{N-}
 ...
 (N+1) : if $\Delta r_p(k)$ is A_0 then $\Delta u_p(k)$ is C_0
 ...
 (2N+1) : if $\Delta r_p(k)$ is A_{N+} then $\Delta u_p(k)$ is C_{N+} (23)

Here, we consider how to determine parameters of the position and the width of each MF for antecedent and consequent with GA.

In order to find these parameters of fuzzy preview control element with GA technique, MFs should be defined at first. The MFs for antecedent are defined as uniform, and the range of fuzzy universe is $[-H_N,$

$H_N]$, as shown in Fig. 7. Because it is uniform, both the position and width are determined by H_N . The MFs for antecedent are defined as:

$$\begin{cases} A_{i\pm} : \left[\pm(i-1)\frac{H_N}{N}, \pm i\frac{H_N}{N}, \pm(i+1)\frac{H_N}{N} \right], \\ \quad \quad \quad i=0, \dots, N-1 \\ A_{N\pm} : \left[\pm(N-1)\frac{H_N}{N}, \pm H_N, \pm \infty \right] \end{cases} \quad (24)$$

where, A_i is the intermediate linguistic variable (such as NS, PM), and A_N is the extreme linguistic variable (such as PB, NB).

The definition of MFs for consequent is shown in Fig. 8 and Fig. 9 in detail. According to the figure, the MFs for consequent are described as: (1) the range is $[-x_N, x_N]$, (2) although the MFs for consequent are symmetrical with Y-axis, the MFs are not uniform, and the positions of the MFs will be optimized with GA. They are defined as

$$\begin{cases} C_{i\pm} : \left[\pm\left(x_i - \frac{x_N}{N}\right), \pm x_i, \pm\left(x_i + \frac{x_N}{N}\right) \right], \\ \quad \quad \quad i=0, \dots, N-1 \\ C_{N\pm} : \left[\pm\left(x_N - \frac{x_N}{N}\right), \pm x_N, \pm \infty \right] \end{cases} \quad (25)$$

where $C_{i\pm}$ is the intermediate linguistic variable, and $C_{N\pm}$ is the extreme linguistic variable. According to Eq. (25), we see that the width of the MF is determined based on the range of fuzzy universe. Here, we defined $C = [C_{N-1} \dots C_{i-} \dots C_0 \dots C_{i+} \dots C_N]$.

To preview control element, it is not enough to

Fig. 7 Membership Functions for antecedent

Fig. 8 Membership Functions for consequent

Fig. 9 Membership Functions for consequent in detail

design the FLC only, but how to determine preview step number L_p is also important. A suitable L_p can not only let the response of system be faster and less overshoot, but also make the response track the ramp input almost without steady-state velocity error, which means the control system is type-II-like. Here L_p is designed with GA together with $FLC-P$. The training algorithms for fuzzy preview control element are as follows:

(1) The parameters include H_N for antecedent, $\{x_1, \dots, x_N\}$ for consequent, and preview step number L_p . Coding method is shown in Eq. (26), for example. Their range determines the string's length of each variable.

$$\begin{array}{ccc} \overbrace{10 \cdots 0}^{H_N} & \overbrace{01 \cdots 0 \cdots 11 \cdots 0}^{x_1 \cdots x_N} & \overbrace{00 \cdots 1}^{L_p} \\ \text{Antecedent} & \text{Consequent} & \text{preview step} \end{array} \quad (26)$$

(2) Initial generation is set with randomly generating an initial population.

(3) Yield measure of each chromosome according to the performance criteria as Eq. (20).

(4) Create next generation with crossover and mutation.

(5) Generate next generation with reproduction.

(6) The GA run iteratively repeating the process (3) - (5) until it arrives at a predetermined ending condition.

5. Experiments with the Fuzzy I-PD Preview Control

5.1 Experimental equipment

Figure 10 shows a two-cascaded tank system with pure time delay. Tank 2 in above is a straight tank, and its cross-sectional area is A_2 . Tank 1 in below is an inclined tank that the sidewall is not straight. Its cross-sectional area is changed with the water level. The inclined angle of its sidewall is β , and the width of Tank 2 is L . The time delay of this system is about 1 second. In this figure, $u_r(t)$ is the command signal of flow control element, $u(t)$ is the flow rate detected by electromagnetic flow meter, $y(t) = x_1(t)$ and $x_2(t)$ are water level of the below tank and above tank respectively. The water level of each tank is detected with differential transducer and 1 [V] is about 7.24 [cm].

According to the Daniel Bernoulli's hydrodynamics theory, we have the nonlinear differential equations of the two-cascaded tank system as

$$\begin{cases} \dot{x}_1 = -\frac{\gamma_1 \sqrt{2gx_1} + \gamma_2 \sqrt{2gx_2}}{2(d + x_1 \tan \beta)L} \\ \dot{x}_2 = -\frac{\gamma_2 \sqrt{2gx_2}}{A_2} + \frac{1}{A_2} u(t - T_d) \end{cases} \quad (27)$$

Fig. 10 Schematic digraph of two-cascaded tanks system

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (28)$$

When there are equilibriums at $x_{10} = 8.57$ [cm], $x_{20} = 11.8$ [cm], and $u_0 = 45.8$ [cm³s⁻¹], the parameters are $A_2 = 85$ [cm²], $\gamma_1 = 0.3539$ [cm²] and $\gamma_2 = 0.3027$ [cm²], and $g = 9.8$ [ms⁻²] is acceleration of gravity, $T_d = 1$ [s] is the delay time, and those of inclined part of tank 1 are $L = 12$ [cm], $\beta = 5.1^\circ$, and $d = 3.32$ [cm].

Since a tank can be approximated as 1st-order lag system, by experiment with step response at the equilibrium for each tank we got the time constants of two tanks, $T_1 = 43$ [s] and $T_2 = 50$ [s].

Considering the time delay and the dynamics of flow control element, the transfer function of the tank system can be shown as

$$G_p(s) = \frac{1}{4850.1s^2 + 209.8s + 2.371} \cdot \frac{15e^{-s}}{s^2 + 5s + 15} \quad (29)$$

where the $15e^{-s}/(s^2 + 5s + 15)$ is the transfer function of both the time delay and the flow control element.

Using the Maclaurin's series for e^{-s} , Eq. (29) can be changed as Eq. (3), and a'_i is shown in

$$\{a'_i\} = \{2.67 \ 260.95 \ 6489.62 \ 8424.76 \ 5632.93\} \quad (30)$$

With this linear model, we can design the FIC matching with I-PD Control.

5.2 Experiments for Fuzzy I-PD control and I-PD control

First, we use the FLC whose MFs for consequent is MFZ and adjust k_c and k_σ to compensate the nonlinear property of the plant. The string lengths of both k_c and k_σ are 16, where $k_{\sigma 1} = k_{c1}$ and $f_\sigma = f_c = 4$ in Eqs. (18) and (19). The minimum turning precision is $4/(2^{16} - 1) = 0.000061$. The sampling time is $\tau = 5$ [s], and the nonlinear simulation uses four steps Runge-Kutta to Eqs. (27) and (28).

The reference model of the I-PD preview control

system should be 4th-Butterworth-Pattern, because the I-PD preview control system can be designed only with Butterworth-Pattern⁽¹⁸⁾. Here α_i of 4th-Butterworth-Pattern in Eq.(4) is

$$\{\alpha_i\}=\{1, 1, 0.5, 0.146\,5, 0.021\,45\} \quad (31)$$

Designed parameters of I-PD controller are $\tilde{f}_0^*=42.89$, $\tilde{f}_1^*=-30.41$, and $\tilde{k}^*=1.63$.

Meanwhile, when designed FIC, we can select a reference model freely. To get an optimal result, we select the ITAE minimum model⁽³⁾, and α_i is

$$\{\alpha_i\}=\{1\,1\,0.4664\,0.1067\,0.01882\} \quad (32)$$

The maximum reference input is $R=5.07$ [cm] ($R_v=0.7$ [V]). After 50 generations with GA, a good pairs of $k_c=1.124$ and $k_\sigma=1.053$ are generated, and other designed parameters of the FIC are $s_1=0.196\,9$, $s_2=1.540\,9$, $s_3=4.346\,2$ and $k_f=11.714\,7$.

Because the approximate linear model is obtained from step response at the equilibriums, the linear model will change with the water level. To illustrate the FIC can work better than the I-PD control, we do two kinds of experiments (step and ramp) with different step amplitude R . And also, we add the disturbance as $du_r=0.4$ [V] at time=1250 [s] to examine the difference of two control systems.

Fig. 11 Experimental results to step reference input without preview control ($R=2.18$ [cm])

Fig. 12 Experimental results to ramp reference input without preview control ($R=2.18$ [cm])

The experimental results of $R=2.18$ [cm] ($R_v=0.3$ [V]) are shown in Figs. 11 and 12. The responses of the I-PD control system and the FIC system to step and ramp show that they have not big difference. In Figs. 13 and 14, the time responses of $R=5.07$ [cm] ($R_v=0.7$ [V]) is shown with I-PD control system and FIC. We see that the results of the FIC are better than those of the I-PD control.

5.3 Experiments for Fuzzy I-PD preview control and I-PD preview control

The I-PD preview control is designed with the method proposed in Ref.(18). Matching with optimal preview-servo system, the preview control coefficients F_r is

$$F_r = \begin{bmatrix} 1.63 & 1.63 & 1.62 & 1.59 & 1.55 & 1.48 \\ 1.37 & 1.25 & 1.10 & 0.93 & 0.76 \end{bmatrix} \quad (33)$$

and preview step number is 11.

In the FIPC system, the preview control element is designed with GA. At first the parameters should be encoded into a long string as Eq.(26). To fuzzy universe H_N of antecedent, 12 bits was defined to standardize the range [0 409 5]. To adjust them more finely, all the decoding number will be divided by 100. So the fuzzy universe of antecedent is in range

Fig. 13 Experimental results to step reference input without preview control ($R=5.07$ [cm])

Fig. 14 Experimental results to ramp reference input without preview control ($R=5.07$ [cm])

$[-40.95 \ 40.95]$. To consequent, position of each linguistic variable shown in Eq.(25), was represented as 10 bits from 0 to 1 023. In the same way as antecedent, the decoding number will be divided also by 100, and the adjusting range is $[-10.23 \ 10.23]$. The preview step number L_p is defined in 5 bits, and the range is $[0 \ 31]$. We select the number of memberships for antecedent and consequent as $N=4$. Parameter of Gaussian function for weights in Eq.(22) is $\delta=8$.

The parameters for GA are set as: Initial population size is 50; Crossover probability is 0.4; Maximum number of generation is 100; and Basic mutation rate is 0.008. In this two-cascaded tank system, the performance is measured using criteria shown in Eq.(20), and where $\rho=0.01$ and $\gamma=50$. Here, we design fuzzy preview control element to let the control system hold better follow-up property for both step and ramp reference inputs. However, since the ranges of $\Delta r_p(k)$ for step reference input and ramp reference input have big difference, the fuzzy preview controller designed for step reference input is not suitable to ramp reference input, and vice versa. Therefore, we considered a union signal including ramp and step to be the reference input when designed the fuzzy preview control elements. The experiment is done with $R=5.07$ [cm]. After 100 generations optimized by GA, FLC_P was obtained which is $H_N=14.92$ and $C=[-3.7 \ -2.2 \ -1.2 \ -0.7 \ 0 \ 0.7 \ 1.2 \ 2.2 \ 3.7]$ and preview step number is 12. The results are shown in Figs. 15 and 16.

From the experiments to tank system, we can see the effectiveness of the FIPC. As shown in Figs. 11 and 12, when the amplitude of reference input is small (2.18 [cm]), the linear control as I-PD control and I-PD preview control designed with the approximate linear model at the equilibrium point can do a well control to the nonlinear plant. As shown in Figs. 13 and 14, however, when the amplitude of reference input is big (5.07 [cm]), because of the nonlinear properties of the plant, the responses of the I-PD control system have big overshoot and long settling time. The FIC system shows a better response than the I-PD control system. In the response with preview control, shown in Fig. 15, the FIPC system has faster response and smaller overshoot than the I-PD preview control system. And also, in Fig. 16, the I-PD preview control system cannot track the ramp input well, while the FIPC system can do well. Moreover, as shown in Fig. 12 when the water level is low, the disturbance responses of both the FIC system and the I-PD control system are almost the same. But, in a high water level, as shown in Fig. 14, being influenced by the nonlinear properties of the plant, the FIC system can do better than the I-PD control system

Fig. 15 Experimental results to step reference input with preview control ($R=5.07$ [cm])

Fig. 16 Experimental results to ramp reference input with preview control ($R=5.07$ [cm])

under the disturbance. From the experiments above, the steady state responses of the systems with preview control and without preview control are almost the same, because the preview control is a feedforward control and its control effect in the steady state is not big in comparison with feedback control.

6. Conclusions

In this paper, we proposed two new approaches based on fuzzy control. One is the FIC which is a FLC designed with matching technique and modified. The other is how to apply the fuzzy control to preview control. Both of these approaches are devised to be simple as much as possible.

A motivation of our research was in the point that nonlinear property of FLC might result in better control performances to nonlinear plants. From the experimental results with two-cascaded tanks system, we could find the efficacy of our approach. And also, there are many nonlinear elements in process control such as saturation and dead zone. Although only one kind of nonlinear plant dynamic is discussed in this paper, we think that this approach is also effective to other types of nonlinear elements, if the

non-linearity is not very strong and can be simulated with computer.

Actually, most nonlinear dynamics of plants cannot be obtained theoretically. We should find some methods to identify the plants, and use these models of plants to calculate the response of the control system. As the future topic of this research, Neural Network is applied to identify the nonlinear plant. Instead of the nonlinear dynamics obtained theoretically here, the nonlinear model identified by Neural Network will be applied to design the control system.

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