# The Smith-PID Control of Three-Tank-System Based on Fuzzy Theory

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***Abstract*—According to the character of the volume-lag of the controlled process of three-tank-system, Smith predictor was adopted to compensate three-tank-system fuzzy adaptive control system. Fuzzy adaptive Smith predictive control system is composed with Smith predictor and fuzzy adaptive controller. The PID parameters were setting on line. This algorithm uses fuzzy adaptive PID control to improve the resistance ability to random disturbance and Smith predictive control to overcome the time-delay character of controlled object. Simulation results showed that this control algorithm has the advantages of strong adaptive ability and noise immunity.**

***Index Terms* -fuzzy control, adaptive, Simth-PID, three-tank-system**

## I. Introduction

As shown in [1], the controlled process of three-tank-system has obviously character of volume-lag. Due to the complexity of the controlled object, traditional PID control can't satisfy the control requirements of the system. Smith—PI controller was used in [1]. Because the parameter $K_p$ and $K_i$ were man-set, the control effect was not satisfactory. Fuzzy adaptive controller was used in [2]. The random disturbance was inhibited effectively, but the control effect should be improved because of the delays of the system. The schemes of the control of the three-tank-system are mainly the two above by now.

In recent years, the research of advanced control was increase day by day, and fuzzy adaptive control is one of them. Fuzzy adaptive control which is often composed into synthetic controllers with other control schemes has great potential for the control of nonlinear and uncertain systems. A fuzzy adaptive controller was designed in [3] based on the dynamic model and the kinematic controller of the mobile robot of non-holonomic constraint. The controller can overcome the influence of the disturbance and the unknown of the parameters of the robot model[3]. Fuzzy adaptive controller was applied to the reconfigurable manipulator in [4]. The fuzzy adaptive system can approximate the dynamic model of the subsystem well. Fuzzy adaptive sliding mode control scheme and it's strengthen scheme were used in uncertain systems and nonlinear uncertain systems in [5] and [6]. Fuzzy adaptive control was applied to the control system of DC motor in [7], which can overcome disturbance effectively. The stability of the closed-loop system was proved with the use of Lyapunov analysis. A fuzzy adaptive controller was proposed in the control of wheeled inverted pendulums in [8]. Based on Lyapunov synthesis, the fuzzy control ensures that the system outputs track the given bounded reference signals to within a small neighborhood of zero, and overcome disturbance effectively. In addition, fuzzy adaptive control was used in nonlinear SISO systems[9,10,11] and MIMO systems[12,13], and obtained ideal control effects.

The traditional Smith controller can control the delay system effectively. The fuzzy control is changing the human fuzzy language to the machine language that computers can distinguish and controlling the complex object through processing the fuzzy information according to the human experience. So, the fuzzy controller has good control effect to the system with random disturbance. The fuzzy adaptive control and Smith predictive control are combined together in this paper, which improves the robustness of Smith control greatly.

## II. Problem Description

### A. Controlled Object Description

Shanghai new Aotuo three-tank-system is a nonlinear coupling controlled model with multi-input and multi-output. The subject of the experimental device is composed by the three same columniform tanks which are made by transparent organic glass, a reservoir, and corresponding actuator and sensors. Such as Figure1, T1, T2 and T3 are three water containers. V1, V2 and V3 are junction valves between any two of them. V7 and V8 are two adjustable proportional valves. The water is injected into T1 and T2 through pumps P1 and P2. V4, V5 and V6 are three manual regulating valves, which can discharge

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the water of the three containers into tank. Through setting the open or close state of the six manual valves, different object models can be combined.

In this system, the manual valves V4, V5 and V6 are closed, pump P2 are closed, and the manual valves V1, V2 and V3 are adjusted to the appropriate opening (demanding that: V1>V2>V3). The liquid in the reservoir is extracted by pump P1, injected into the container T1 through the proportional valve V7, and then the liquid injected into the container T3 through the manual valve V1, reached container T2 through manual valve V2, and injected into the reservoir through the manual valve V3. In the object model, the input variable is the flow $Q_1$ which is injected into container T1, the controlled variable is the liquid level $h_2$ of the container T2. That composes the three-tank-control-system. The system is single-input single-output third-order object model with volume time-delay.

The control schematic diagram of three-tank-system is shown in Figure 1.

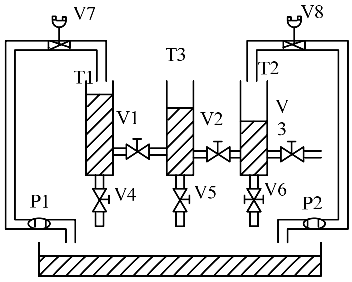


Figure 1. The schematic diagram of the control device of three-tank-system

### B. Mathematical Modeling

Variables and parameters are defined as below: hi-liquid level, $Q_{ij}$-flow, $Q_1$-inflow, A-cross sectional area of the container, Ri-liquid resistance of the manual valve Vi, i=1,2,3; $(i,j)\in\{(1,3);(3,2);(2,0)\}$. $Q_{13}$ represents the flow from T1 to T3, $Q_{32}$ represents the flow from T3 to T2, and $Q_{20}$ represents the flow from T2.

The total delay time of the three-tank-system is τ, and the volume time-delay of each container is τ/3. Suppose that the flow injected into T1 is $Q_1(t)$. Because the volume time-delay of the container T1 is τ/3, its liquid level can be expressed as $h_1(t-\tau/3)$. The flow from T1 to T3 is expressed as $Q_{13}(t-\tau/3)$. Because the volume time-delay of the container T3 is τ/3, its liquid level of T3 can be expressed as $h_3(t-\tau/3)$. The flow from T3 to T2 is expressed as $Q_{23}(t-2\tau/3)$. The output liquid level of T2 is $h_2(t-\tau)$. The flow of T2 is $Q_{20}(t-\tau)$. In this system, the inflow $Q_1$ is input of the controlled process, The liquid level $h_2$ of T2 is the output, and the mathematical model is the mathematical expression between $h_2$ and $Q_1$. Three balance equations of T1, T2 and T3 are established:

$$A\frac{dh_1(t-\frac{\tau}{3})}{dt}=Q_1(t)-Q_{13}(t-\frac{\tau}{3}) \quad (1)$$

$$A\frac{dh_3(t-\frac{2\tau}{3})}{dt}=Q_{13}(t-\frac{\tau}{3})-Q_{32}(t-\frac{2\tau}{3}) \quad (2)$$

$$A\frac{dh_2(t-\tau)}{dt}=Q_{32}(t-\frac{2\tau}{3})-Q_{20}(t-\tau) \quad (3)$$

Expressing (1), (2) and (3) in incremental forms:

$$A\frac{dh_1(t-\frac{\tau}{3})}{dt}=\Delta Q_1(t)-\Delta Q_{13}(t-\frac{\tau}{3}) \quad (4)$$

$$A\frac{dh_3(t-\frac{2\tau}{3})}{dt}=\Delta Q_{13}(t-\frac{\tau}{3})-\Delta Q_{32}(t-\frac{2\tau}{3}) \quad (5)$$

$$A\frac{dh_2(t-\tau)}{dt}=\Delta Q_{32}(t-\frac{2\tau}{3})-\Delta Q_{20}(t-\tau) \quad (6)$$

According to fluid dynamics, there is linear relationship between the liquid level and flow in the turbulence situation. Through linear processing:

$$\Delta Q_{13}(t-\frac{\tau}{3})=\frac{\Delta h_1(t-\frac{\tau}{3})}{R_1} \quad (7)$$

$$\Delta Q_{32}(t-\frac{2\tau}{3})=\frac{\Delta h_3(t-\frac{2\tau}{3})}{R_2} \quad (8)$$

$$\Delta Q_{20}(t-\tau)=\frac{\Delta h_2(t-\tau)}{R_3} \quad (9)$$

After Laplace transformation, the mathematical model of the three-tank-system is:

$$W(s)=\frac{H_2(s)}{Q_1(s)} \quad (10)$$

$$W(s)=\frac{K}{(T_1s+1)(T_2s+1)(T_3s+1)}e^{-\tau s} \quad (11)$$

Thereinto, $T_1$ is the time constant of the first container, $T_1=R_1A$; $T_2$ is the time constant of the second container, $T_2=R_2A$; $T_3$ is the time constant of the third container, $T_3=R_3A$; K is the magnification factor, $K=R_3$; τ is the lag time.

Suppose that: the transfer function of the system in this paper can be represented by third-order inertial lag link:

$$W(s)=\frac{2e^{-2s}}{125s^3+75s^2+15s+1} \quad (12)$$

## III. Fuzzy Controller

Fuzzy control is a computer intelligent control based on fuzzy set theory, fuzzy language variable and fuzzy logic inference. The basic conception of fuzzy control is proposed by the famous professor of California University of America L.A.Zadeh at the first time. Passes more than twenty years' development, significant success has been obtained in the aspect of fuzzy control theory and application research.

The basic principle block of the fuzzy control is shown in Figure 2. The core part is fuzzy controller. The control law of the fuzzy controller is realized by the computer program. The process of realization of the fuzzy control algorithm is described as follows: The accurate quantity of

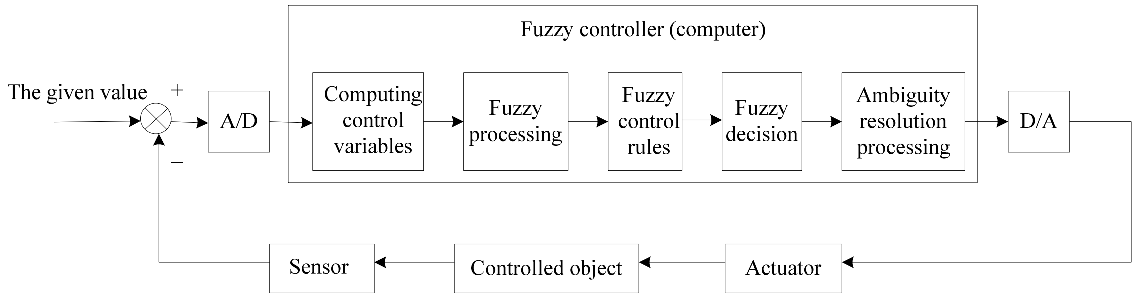


Figure 2. The basic principle block diagram of the fuzzy control

the controlled variable is sample obtained by computer, and then compares the value with the given value to obtain the error signal E which is usually selected as one of the input values of the fuzzy controller. The accuracy value of the error signal E is fuzzed to the fuzzy value. The fuzzy value of the error signal E can be expressed by the corresponding fuzzy language to obtain a subset of the fuzzy language set e (e is a fuzzy vector), and then e and the fuzzy control rule R (fuzzy operator) are used to obtain the fuzzy control value u based on the combination rule of the inference:

$$u = e \circ R \tag{13}$$

The main difference between the fuzzy control system and the usual computer digital control system is that the fuzzy control system adopts fuzzy controller. Fuzzy controller is the core of the fuzzy control system. The performance of the fuzzy control system mainly depends on the structure of the fuzzy controller, the fuzzy rules, the compositional inference algorithm and the fuzzy decision method, ect.

Fuzzy controller is also called fuzzy logic controller. Because the fuzzy control rules are described by the fuzzy condition sentences of the fuzzy theory, the fuzzy controller is a language controller. It is also called fuzzy language controller.

The composition block diagram of the fuzzy controller is shown in Figure 3.

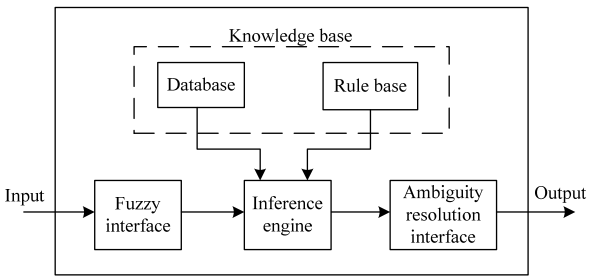


Figure 3. The composition block diagram of the fuzzy controller

Fuzzy interface:

The inputs of the fuzzy controller must be fuzzed to solve the output of the control. So, it is the input interface of the fuzzy controller. Its main role is changing the real input value to a fuzzy vector. For the fuzzy input variable e, its fuzzy subset is usually divided as follows:

e={Negative Big, Negative Small, Zero, Positive Small, Positive Big}={NB, NS, ZO, PS, PB}

e={Negative Big, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Big}={NB, NM, NS, ZO, PS, PM, PB}

e={Negative Big, Negative Middle, Negative Small, Negative Zero, Positive Zero, Positive Small, Positive Middle, Positive Big}={NB, NM, NS, NZ, PZ, PS, PM, PB}

The membership functions are usually expressed using triangles.

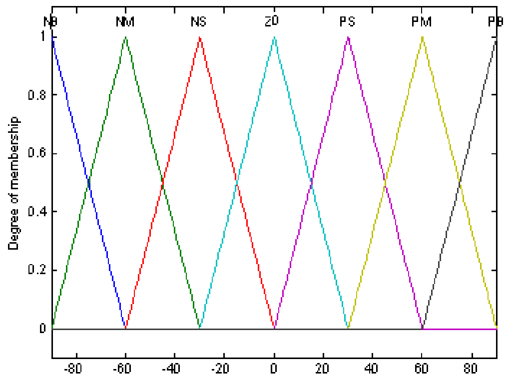


Figure 4. The membership functions of variable

Knowledge Base:

The knowledge base is composed by database and rule base.

Database:

The database stores the membership function vectors of the fuzzy subset of all the input variables and output variables. If the universe is the continuous domain, the database stores membership function. It supplies data for the inference engine in the solving process of fuzzy relationship equations of the rule inference.

Rule base:

The rules of the fuzzy controller are based on the experience of the manual operators or the knowledge of experts. It is a language expression form based on people's intuition. Fuzzy rules are usually connected by a series of relational words, such as if_then, else, also, end and or, ect. The relational words must through translating to make the fuzzy rules numerical. The commonly used relational words are if_then and also. For the multi variable fuzzy control system, the commonly used relational words are and, ect. For example, the input variables of the fuzzy control system are e(error) and $e_c$(error change). Their corresponding language variables are E and EC. A group of fuzzy rules are:

R1: IF E is NB and EC is NB then U is PB

R2: IF E is NB and EC is NS then U is PM

The if… part is usually called "premise part", and the then… part is usually called "conclusion part". Its basic structure can be concluded to: If A and B then C. Thereinto, A is a fuzzy subset of universe U, and B is a fuzzy subset of universe V. According to the manual control experience, the control decision table R can be organized off-line. R is a fuzzy subset of the Cartesian product set U×V. The control value can be expressed as:

$$C = (A \times B) \circ R \quad (14)$$

Thereinto, × is the fuzzy direct product operation. ○ is the fuzzy compose operation.

The rule base is used to store the fuzzy control rules. It supplies control rules for the inference engine. The number of the rules is related to the fuzzy subset division of the fuzzy variables. The accuracy of the rule base is connected with the accuracy of the knowledge of experts.

Inference and Defuzzy-interface:

Inference is the function part of obtaining the fuzzy control values through fuzzy control rules based on the input fuzzy values and the fuzzy control rules. In the fuzzy control, the inference methods with simple operation will be adopted considering the inference time. The most basic inference is Zadeh approximate inference. It includes forward inference and backward inference. The forward inference is usually used in the fuzzy control, and the backward inference is usually used in the expert systems of the engineering fields.

The acquirement of the inference conclusion expresses that the rule inference function of the fuzzy control has been completed. But the result is a fuzzy vector. The accuracy output control value has been obtained through defuzzy. The output terminal with converting function is called Defuzzy-interface.

## IV. Fuzzy Adaptive PID Controller

With the development of computer technology, artificial intelligence method is used to store the adjusting experience of operators to the computer. According to the site actual situation, computer can adjust PID parameters automatically. That is the expert PID controller. The controller combined the classical PID control with the advanced expert system, and realized the optimal control of the system. This control method determines the object model accurately, models the experience of operators, and adjusts PID parameters by inferring.

Because the experience of operators can't be described accurately, and the various semaphores and the evaluation index can't be expressed quantificationally, the expert PID method is limited. Fuzzy theory is the efficient path to solve the problem. The basic theory and methods of fuzzy mathematic are used to construct fuzzy sets to express the conditions of rule and operations. Then, the computer controls the systems based on the actual response condition. Fuzzy adaptive PID control has many kinds of structure forms right now, but their working principles are basically identical.

Fuzzy adaptive PID control is on the basis of PID algorithm, through calculating the error e and the error rate $e_c$ of the current system, reasoning using fuzzy inference rules and adjusting parameters by searching fuzzy matrix tales. In the design of fuzzy adaptive controller, the error e and the error rate $e_c$ of the current system are inputs, which can meets the demand of self-tunning of the PID parameters based on different e and $e_c$ in different time. The fuzzy adaptive controller modifies PID parameters on line based on fuzzy control rules. Its structure is shown in Figure 5.

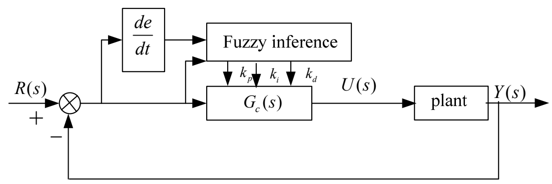


Figure 5.The structure of the fuzzy adaptive controller

The fuzzy adaptive controller is finding the relationship between PID parameters and different e, different rate $e_c$, detecting e and $e_c$ constantly during the operation, and modifying the three parameters on line based on fuzzy control theory to meet different demands of control parameters for different e and different rate ec. In that way, the controlled object has good dynamic and static performance[14].

### A. Fuzzy Inputting Method

Fuzzy controller was adopted in adjusting the proportion parameter $k_p$, integral parameter $k_i$ and differential parameter $k_d$ on line. The different e and different rate ec of input are fuzzed by 7 fuzzy sets. They are "PB", "PM", "PS", "Z", "NS", "NM", "NB". The output proportion parameter $k_p$, integral parameter $k_i$ and differential parameter $k_d$ are fuzzed by 7 fuzzy sets. They are "PB", "PM", "PS", "Z", "NS", "NM", "NB". The discrete universe of e and ec is {-3, -2, -1, 0, 1, 2, 3}. The discrete universes of outputs are: $k_p$ {-0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3}, $k_i$ {-0.06, -0.04, -0.02, 0, 0.02, 0.04, 0.06}, and $k_d$ {-3, -2, -1, 0, 1, 2, 3}. There are 49 fuzzy control rules which are shown in table 1[14].

The fuzzy variables of the fuzzy adaptive controller adopt forms of triangle functions, S mode functions and Z mode functions.

### B. Fuzzy Rules

Consider from the stability, response velocity, overshoot and steady state accuracy, the rules of $K_p$, $K_i$ and $K_d$ are:

The role of proportional coefficient $K_p$ is speeding up the response velocity of system and improving the adjusting accuracy of the system. The bigger the $K_p$, the quicker the response velocity of the system, the higher the

TABLE I. THE FUZZY INFERENCE RULES TABLE OF THE KP, KI ,KD

| e \ $e_c$ ($k_p/k_i/k_d$) | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | Z/Z/NM | Z/Z/PS |
| NM | PB/NB/PS | PB/NB/NS | PM/NM/NB | PS/NS/NM | PS/NS/NM | Z/Z/NS | NS/Z/Z |
| NS | PM/NB/Z | PM/NM/NS | PM/NS/NM | PS/NS/NM | Z/Z/NS | NS/PS/NS | NS/PS/Z |
| Z | PM/NM/Z | PM/NM/NS | PS/NS/NS | Z/Z/NS | NS/PS/NS | NM/PM/NS | NM/PM/Z |
| PS | PS/NM/Z | PS/NS/Z | Z/Z/Z | NS/PS/Z | NS/PS/Z | NM/PM/Z | NM/PB/Z |
| PM | PS/Z/PB | Z/Z/NS | NS/PS/PS | NM/PM/PS | NM/PM/PS | NM/PB/PS | NB/PB/PB |
| PB | Z/Z/PB | Z/Z/PM | NM/PS/PM | NM/PM/PM | NM/PM/PS | NB/PB/PS | NB/PB/PB |

adjusting accuracy of the system, the easier the production of overshoot, and what's more lead to the unstable of the system. If the value of $K_p$ is too small, the adjusting accuracy will be reduced, the response velocity will be slow, the adjusting time of the system will be prolonged, and the static and dynamic characteristics will become worse.

The role of integral coefficient $K_i$ is eliminating the steady-state error of the system. The bigger the $K_i$, the eliminating of the steady-state error of the system is more quickly. If $K_i$ is too big, integral saturation phenomenon will appear in the early stage of the response process and the overshoot of the response process will be big. If $K_i$ is too small, the steady-state error of the system will be hard to eliminate, the adjusting accuracy of the system will be affected.

The role of differential coefficient $K_d$ is improving the dynamic characteristics of the system. The role is mainly inhibiting the deviation changing towards any direction. It can forecast the changing of the deviation. If $K_d$ is too big, the response process will brake in advance, the adjusting time will be prolonged, and the noise immunity of the system will be decreased.

The effects of the three parameters and the relationships between them have to be considered when setting the PID parameters. The relationships among e, $e_c$ and $K_p$, $K_i$, $K_d$ has been concluded as follows:

When |e(t)| is big, $K_p$ should be big too, so that the time constant and the damping coefficient of the system will decrease. The values should be not too big, otherwise, the system will be unstable. To avoid the out of range control of the system in the beginning, $K_d$ should be small. To avoid the big overshoot, $K_i$ can be set to zero.

When |e(t)| is medium sized, $K_p$ should be relatively small. So, the overshoot of the system will be small. The value of $K_d$ is important to the system this time. The value of $K_d$ should be proper to guarantee the response speed of the system. The value of $K_i$ can be increased properly, but not too big.

When |e(t)| is small, the values of $K_p$ and $K_i$ should be bigger to guarantee the good steady performance of the system. The value of $K_d$ should be proper to avoid concussion of the system in the equilibrium.

Based on the relationships among e, $e_c$ and $K_p$, $K_i$, $K_d$ which were summarized above, combined with the analysis and the actual operation experience of the engineers and technicians and considering the effect of the different rate $|e_c(t)|$, table 1 was obtained which are the fuzzy rules of regulating the three parameters of the PID controller[15].

### C. Fuzzy Inference

Inference is the process of accomplishing fuzzy inference and obtaining the fuzzy control variables based on the fuzzy inputs and fuzzy control rules which are used to solve the fuzzy relation equations. Mamdani organum is adopted in this paper. Mamdani organum is a common organum in fuzzy control. It is a compositional rule of inference which takes different form in fuzzy implication relations.

Suppose that the fuzzy condition sentences are:

$\tilde{R}_i$: if x is $\tilde{A}_i$ and y is $\tilde{B}_i$ then z is $\tilde{C}_i$ (i=1,2,3 ⋯ n)

The inference process is:

Calculating the fuzzy implication relations: $\tilde{R}_i$ (i=1,2,3 ⋯ n)

Suppose that: $\tilde{A}_i = (a_1 \quad a_2 \quad \cdots \quad a_m)$ , which is m dimensions row vector. $\tilde{B}_i = (b_1 \quad b_2 \quad \cdots \quad b_n)$, which is n dimensions row vector. $\tilde{C}_i = (c_1 \quad c_2 \quad \cdots \quad c_t)$, which is t dimensions row vector. Calculating the fuzzy relations of the fuzzy sets in the antecedent of $\tilde{R}_i$ : $\tilde{P}_i = \tilde{A}_i \times \tilde{B}_i = \tilde{A}_i^T \wedge \tilde{B}_i$ . Thereinto, $\tilde{A}_i \times \tilde{B}_i$ is the cartesian product of fuzzy vector, and the result is $m \times n$ fuzzy matrix.

Calculating the fuzzy implication relations $\tilde{P}_i \to \tilde{C}_i$ which between the antecedent and consequent of $\tilde{R}_i$. For easy, the fuzzy matrix $\tilde{P}_i$ is straightened to m × n dimensions fuzzy row vector. $\tilde{R}_i = \tilde{P}_i \to \tilde{C}_i = \tilde{P}_i^T \wedge \tilde{C}_i$.

Calculating the total fuzzy implication relation $\tilde{R}$

$$\tilde{R} = \tilde{R}_1 \cup \tilde{R}_2 \cup \cdots \cup \tilde{R}_i \cup \cdots \quad (15)$$

Calculating the fuzzy relation between the new inputs $\tilde{A}'$ and $\tilde{B}'$.

$$\tilde{P}' = \tilde{A}' \times \tilde{B}' \quad (16)$$

Calculating the fuzzy sets of the output value

$$\tilde{C}' = (\tilde{A}' \times \tilde{B}') \bigcirc \tilde{R} = \tilde{P}' \bigcirc \tilde{R} \quad (17)$$

### D. Ambiguity Resolution of the Output

The inference result represents the achievement of the rule inference of the fuzzy control. But the result is still a fuzzy vector. In the actual fuzzy control, there must be a certain value to control or drive the actuator. So, the fuzzy vector obtained through fuzzy inference must be converted to obtain the clear control outputs. This process is called ambiguity resolution.

The selection of ambiguity resolution method is related with the selection of the shape of membership functions and the inference methods. Matlab provides five kinds of ambiguity resolution method: (1) centroid (area centroid method), (2) bisector (area-equal-dividing method), (3) mom (average maximum membership degree method), (4) som (small maximum membership degree method), (5) lom (big maximum membership degree method).

Centroid anti-fuzzy method is adopted in this paper.

To obtain accuracy control variables, the fuzzy method is asked to express the calculation results of the membership degree functions of the outputs. The area centroid method is taking the centroid of the area which is enclosed by the membership degree function curve and the abscissa as the finally output.

$$v_0 = \frac{\int_V v\mu_v(v)dv}{\int_V \mu_v(v)dv} \tag{18}$$

For the discrete filter situation:

$$v_0 = \frac{\sum_{k=1}^{m} v_k \mu_v(v_k)}{\sum_{k=1}^{m} \mu_v(v_k)} \tag{19}$$

Compared with the maximum membership degree method, the area centroid method has more smooth output inference control. The output of the system will change even if the input signal has little change.

The single loop control system with pure delay is shown in Figure 6, whose closed-loop transfer function is shown as follows:

$$\phi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)e^{-\tau s}}{1+G_c(s)G_0(s)e^{-\tau s}} \tag{20}$$

It's characteristic equation is:

$$1+G_c(s)G_0(s)e^{-\tau s} = 0 \tag{21}$$

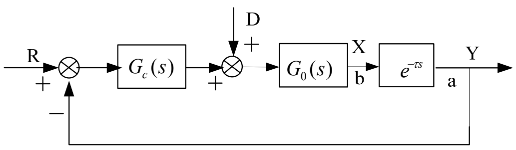


Figure 6. The single loop control system with pure delay

Obviously, there is pure delay in the characteristic equation. If τ is big enough, the system will be unstable. That is the essence that the long time delay process is hard to control[9]. $e^{-\tau s}$ appears in the characteristic equation, because the feedback signal is cited from point a of the system. If the feedback signal is cited from point b, the pure delay part is removed outside of the control circuit. As shown in Figure 7. After time delay τ, the controlled variable Y will repeat changes of X.

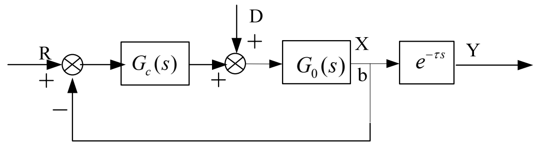


Figure 7. Improved single loop control system with pure delay

Because the feedback signal X has no delay, the response of the system is greatly improved. Point b is not exist or limited by the physical conditions in the practical system. So, the feedback signal can't be cited from point b. According to this problem, Smith proposed artificial model method. The structure is shown in Figure 8.

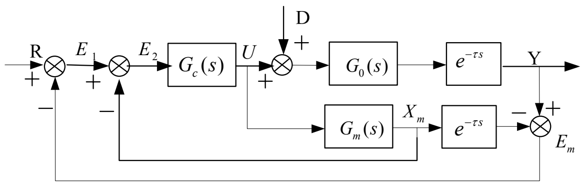


Figure 8. Smith predict control system

If the model is accurate, such as $G_0(s) = G_m(s)$, $\tau=\tau_m$, and there is no load disturbance(D=0). $Y=Y_m$, $E_m=Y-Y_m=0$, $X=X_m$. So, $X_m$ can change X as the first feedback loop and the pure delay part is moved outside of the control loop. If the model is inaccurate or there is load disturbance in the control process, X is not equal to $X_m$, $E_m=Y-Y_m \neq 0$, and the control precision is not a great satisfaction. So, $E_m$ is used to realize the second feedback loop. This is the control strategy of Smith predictor controller[15].

## V. FUZZY ADAPTIVE SMITH CONTROLLER

The pute Smith predictive controller compensates the delay part of the time-delay system. Its PID control demands that the system must have accuracy transfer function. For the plant model with time-varying transfer function or time-varying parameters, Smith predictive controller can't achieve the ideal control effect. What's more, the Smith predictive controller is sensitive to the error. If the error is too big, the control effect will be decreased. Because the fuzzy adaptive controller adopts fuzzy set theory, it has some tolerance degree to the interference factors of itself and external. It allows the transfer function of the controlled object varying with time. The fuzzy adaptive control can work effectively whether the controlled object is linear or nonlinear. The combination of Smith predictive controller and fuzzy adaptive controller can control the overshoot of the system effectively and achieve a good control effect.

If the pute fuzzy adaptive controller is used to control the large time-delay system, the concussion of the system will be exacerbated, the adjusting time will be prolonged, and the control performance will become worse, because the control variables will have effect on the controlled object after a long time. The control variable must be responded in advance. If the Smith predictive controller is added, the delay time of the system is compensated; the control variable can control the controlled object in real time, and the ideal control effect will be obtained.

The control problem of the pure delay time-varying system can be solved effectively when fuzzy adaptive PID controller is combined with Smith predict controller. The adjusting time of the system will be shortened, the concussion and the overshoot of the system will be eliminated, the anti-interference ability will be enhanced, and the robustness and adaptive ability will be improved. The structure of the control system is shown in Figure 9.

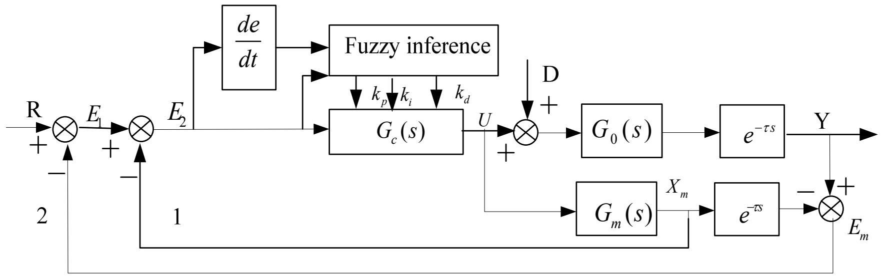


Figure 9. Fuzzy adaptive Smith-PID control system

The basic principle of the method is that: fuzzy control is used to adjust the parameters $k_p$ 、 $k_i$ 、 $k_d$ of the PID controller $G_c(s)$. The output of the PID controller $G_c(s)$ is shown as follows:

$$u(k)=u(k-1)+k_p[e'(k)-e'(k-1)]+ k_i e'(k)+k_d[e'(k)-2e'(k)+e'(k-2)] \quad (22)$$

In the equation (21), $k_p$ is proportion parameter, $k_i$ is integral parameter, and $k_d$ is differential parameter. u(k) is the output of the controller in the k th sampling time, and u(k-1) is the output of the controller in the (k-1) th sampling time.

$$e'(k)=E_m(k) \quad (23)$$

If the model of the controlled object is accurate, and there is no load disturbance, the first feedback loop should be used, m=2. Otherwise, the second feedback loop should be used, m=1.

## VI. FUZZY ADAPTIVE SMITH CONTROL SIMULATION

The mathematical model of one three-tank-system is $W(s)=\dfrac{2e^{-2s}}{125s^3+75s^2+15s+1}$. The simulation process was performed as follows: Smith—PI method, fuzzy adaptive PID method, and fuzzy adaptive Smith—PID method were used in this paper. One unit pulse interference signal was added in the middle of the simulation process. The simulation was carried with MATLAB7.4.0. The graph of the fuzzy inference system is shown in Figure 10. The graph of the membership functions of the fuzzy adaptive PID controller is shown in Figure 11~15. The curves of the outputs of the fuzzy adaptive PID controller are shown in Figure 16~18.

The values of $K_p0$ and Ki0 were taken as 0.5 and 0.05 when taking the method of Smith—PI. The values of $K_p0$, $K_i0$ and $K_d0$ were taken as 0.5, 0.042 and 1.4 when taking the method of fuzzy adaptive Smith—PID. The step response curves of the system with the method of Smith—PI and fuzzy adaptive PID were shown in Figure 19 and Figure 20. The step response curve of the system with the method of fuzzy adaptive Smith—PID was shown in Figure 21.

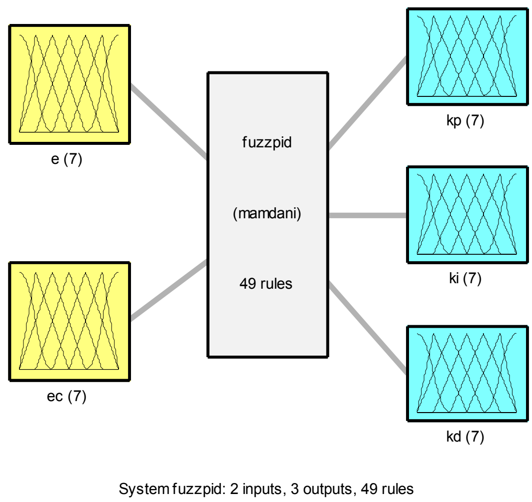


Figure 10. Fuzzy inference system

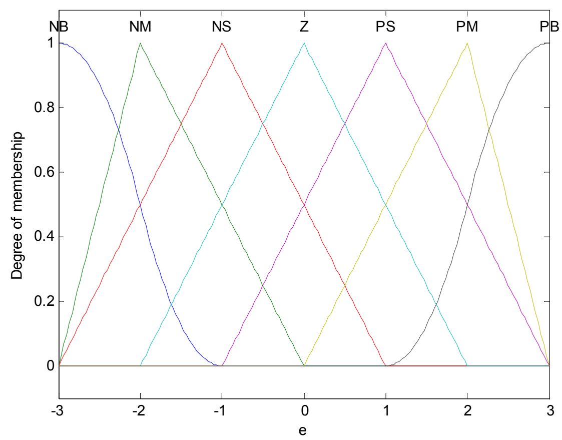


Figure 11. The membership function of input e

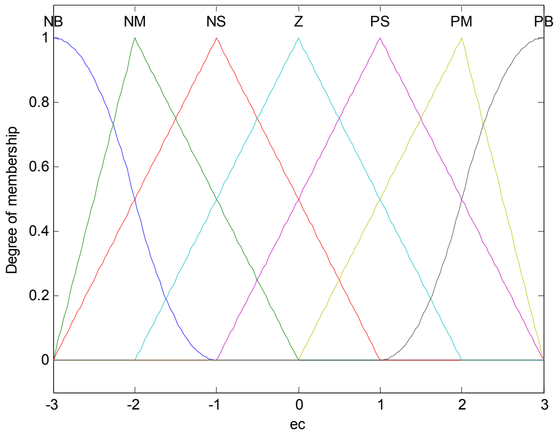


Figure 12. The membership function of input ec

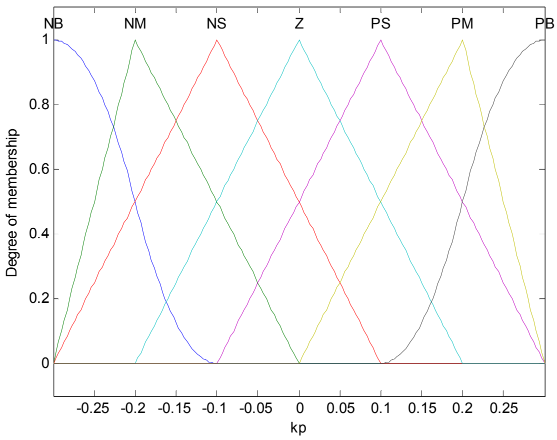


Figure 13. The membership function of output $K_p$

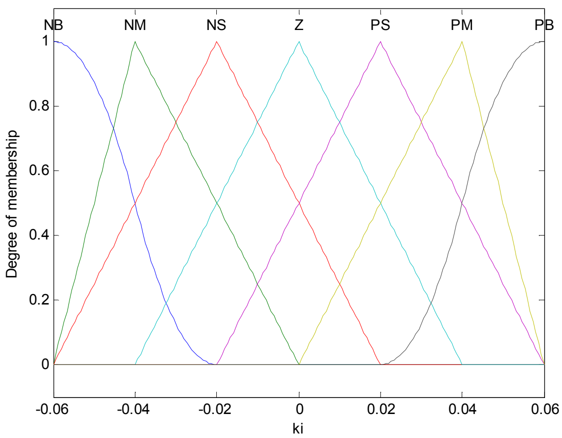


Figure 14. The membership function of output $K_i$

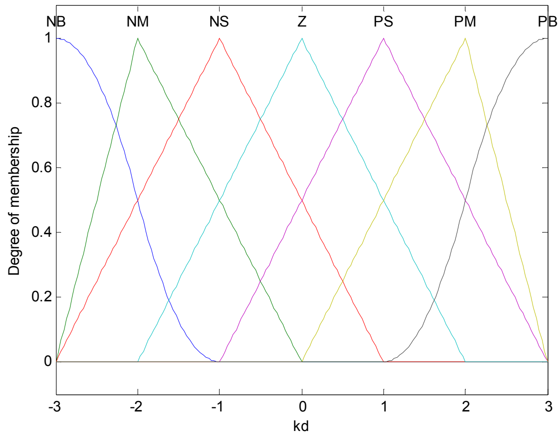


Figure 15. The membership function of output $K_d$

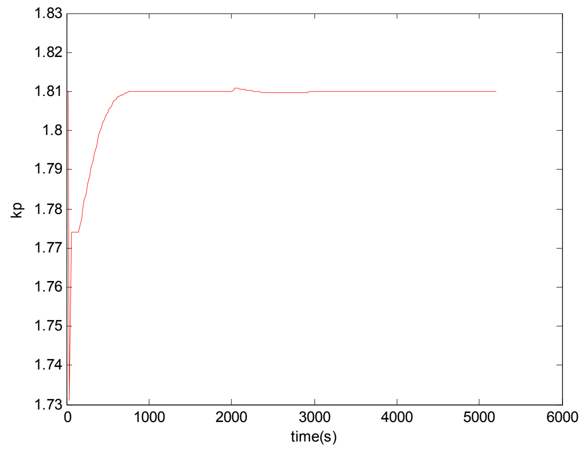


Figure 16. The curve of the output $K_p$ of the fuzzy adaptive PID controller

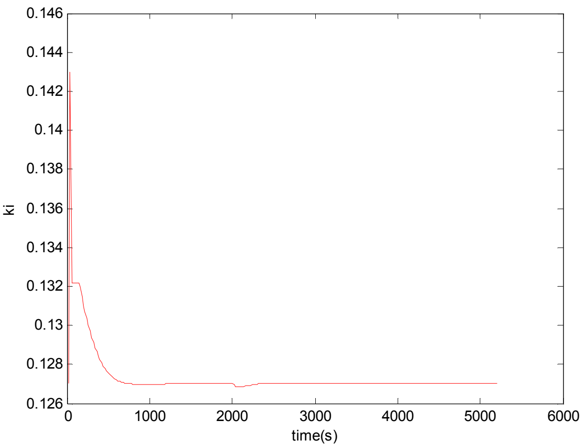


Figure 17. The curve of the output $K_i$ of the fuzzy adaptive PID controller

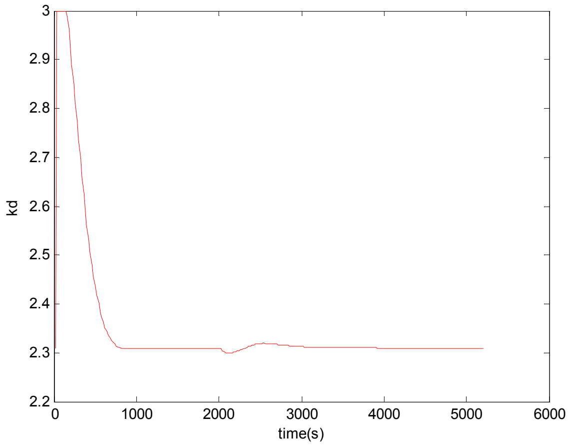


Figure 18. The curve of the output $K_d$ of the fuzzy adaptive PID controller

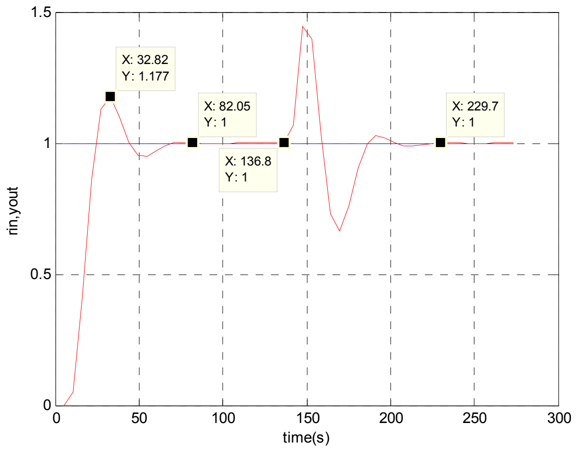


Figure 19. The output curve of the system with Smith—PI method

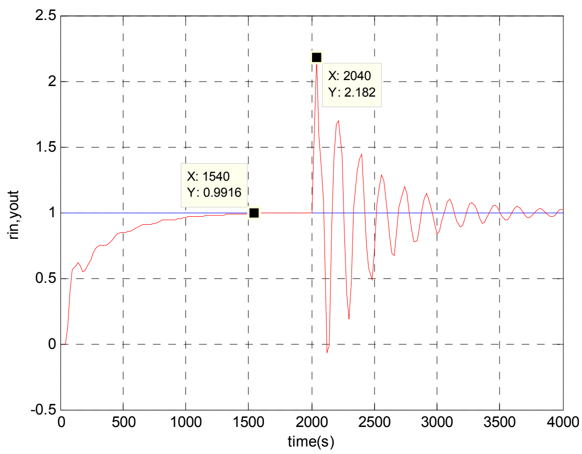


Figure 20. The output curve of the system with fuzzy adaptive PID method

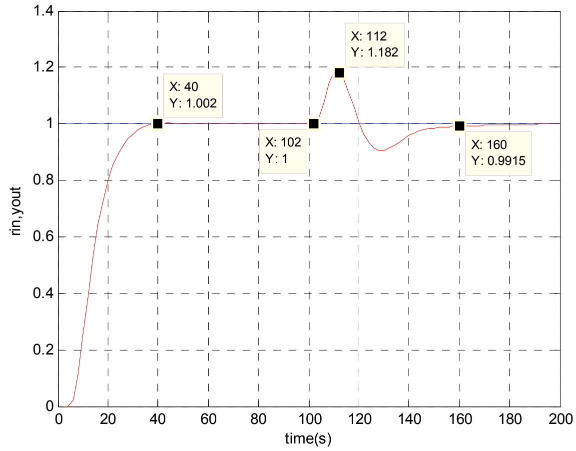


Figure 21. The output curve of the system with fuzzy adaptive Smith—PID method

The figures show that: the response process of the system has no overshoot when using the method of fuzzy adaptive Smith—PID, and can reach stable in 40s. The response process of the system has big overshoot when using the method of Smith—PI, and can reach stable in 82s. The response process of the system has no overshoot when using the method of fuzzy adaptive PID, and can reach stable in 1540 s. For anti-interference, the system has better reaction effect when using the method of fuzzy adaptive Smith—PID. The simulation shows that the method of fuzzy adaptive Smith—PID can solve the contradiction of the rapidity and the stability.

## VII. CONCLUSIONS

Fuzzy adaptive Smith predictor was used to control three-tank-system with delay in this paper. The fuzzy adaptive PID part can improve the resisting ability and adaptive ability of the system to random disturbance, and the Smith predict control part can overcome the delay characteristic of the controlled object. MATLAB7.4.0 is used as development platform and three-tank-system as research object in this paper. Smith—PI method, fuzzy adaptive PID method, and fuzzy adaptive Smith—PID method were used in the simulation. The simulation results show that fuzzy adaptive Smith—PID method can make the system has better adaptive ability, shorter settling time, better stability, and stronger anti-interference ability.

## ACKNOWLEDGMENT

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