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Analysis and Design of Fuzzy Logic Control Systems*

YU Dejiang
(Department of Mechanical Engineering, The Hong Kong Polytechnic University · Hong Kong)
MAO Zongyuan and ZHOU Qijie
(Department of Automatic Control Engineering, South China University of Technology · Guangzhou, 510641, PRC)

Abstract: In this paper the stability of the closed-loop fuzzy logic control system is analyzed using L_p stability and circle criterion based on the suggestion that considers fuzzy logic controller as a multidimensional relay. The stability criteria and the design method for the closed-loop nonlinear system associated with fuzzy logic controller are given. The application of the stability conditions to different systems are further studied through computer simulations.

Key words: Fuzzy logic control; nonlinear systems; L_p-stability; circle criterion

1 Introduction

Fuzzy logic method has found its wide range of applications, especially in the field of control engineering. The stability analysis is a very important issue encountered when designing a control system but it was difficult for the fuzzy control system before. The reason is that the fuzzy system is complex to analyze with the control theory since the fuzzy controller cannot be described with an mathematical model analytically and precisely.

Recently several practical and theoretical methods have been developed for analyzing the fuzzy logic control system[1~8]. Kickert W. J. M. and Mamdani E. H[1]. treated fuzzy logic controller as a multilevel relay that reduces the controller to a conventional nonlinear one and the particular stability analysis was based on the describing function technique. Followed by Ray, Kumar S. Ghosh Ananda M. and Majumder, D. Dutta [2,3], the concept of the well-known L_2-stability and the circle criterion were used to study the fuzzy logic system. Their analogy provides a basis for the stability analysis of a closed-loop system under fuzzy control. In the above methods the great advantage is that the fuzzy logic controller is considered as a multilevel relay. However, for the general situation of multi-input and single-output of the fuzzy controller, they did not give a general result.

In fact a real fuzzy control system is often of the type of PI(PD) or PID and the controller can be considered as a multidimensional relay with the error and the increment of error as its inputs. Therefore, a fuzzy logic control system with PI(PD) controller, for example, can be depicted as shown in Fig. 1. Here fuzzy controller is with two inputs and one output and in this sense the control-

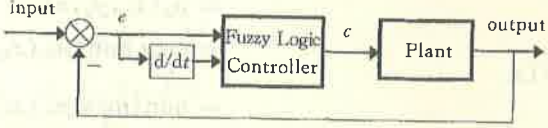

Fig. 1 A PI(PD) fuzzy logic control system

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ler can be considered as a two-dimensional relay discussed below. We focus attention on the analysis of fuzzy controllers and the stability of the closed-loop system associated with the fuzzy logic.

2 Fuzzy Logic Controller

The fuzzy PI control algorithm is based on such a set of inferring rules:

If E is A_i and If ΔE is B_j Then ΔU is C_{ij}, $I = 1,2,\cdots,n, j = 1,2,\cdots,m$,

where inputs E and ΔE are error $e(k)$ and the change of error $\Delta e(k) = e(k) - e(k-1)$; output ΔU is the inferred increment of control action $\Delta u(k)$; A_i and B_j are fuzzy inputs sets defined over input support sets X and Y respectively: C_{ij} is fuzzy subset of the controller's output in the universe of discourse Z.

The statements in rules infer a relation R that is a fuzzy set defined in the Cartesian Product Space $X \times Y \times Z, R \in F(X \times Y \times Z)$ with its membership function denoted by:

$$\mu_R(x,y,z) = \min[\mu_{Ai}(x);\mu_{Bj}(y);\mu_{Cij}(z)], \quad x \in X, y \in Y, z \in Z. \tag{1}$$

Given the inputs A_t and B_t at time t, the corresponding output C_t can be inferred by $C_t = (A_t \times B_t) \circ R$. Here " $\circ$ "denotes composition of inference. The membership function is determined by:

$$\begin{aligned}\mu_{Ct}(z) &= \max_{x,y} \min\{\mu_{At\times Bt}(x,y);\mu_R(x,y,z)\} \\ &= \max_{x,y} \min\{\mu_{At}(x);\mu_{Bt}(y);\mu_R(x,y,z)\}.\end{aligned} \tag{2}$$

In the fuzzy control system the inputs at time t are measured quantities, so they can be treated as "degenerated"fuzzy set $A_t(B_t)$ with all membership values $\mu_{At}(x)(\mu_{Bt}(y))$ equal to zero, except the value at the measured point $x_0(y_0)$: $\mu_{At}(x_0)(\mu_{Bt}(y_0))$ which is equal to one. It can be stated as:

$$\mu_{At}(x) = \begin{cases} 1, & x = x_0, \\ 0, & x \neq x_0, \end{cases} \tag{3}$$

$$\mu_{Bt}(y) = \begin{cases} 1, & y = y_0, \\ 0, & y \neq y_0. \end{cases} \tag{4}$$

Substituting expression (1), (3)and(4)into (2) results in a simplified fuzzy control algorithm:

$$\begin{aligned}\mu_{Ct}(z) &= \max_{x,y} \min\{\mu_{At}(x);\mu_{Bt}(y);\mu_R(x,y,z)\} \\ &= \min\{\mu_{At}(x_0);\mu_{Bt}(y_0);\mu_R(x_0,y_0,z)\} \\ &= \mu_R(x_0,y_0,z) \\ &= \max_{i,j} \min\{\mu_{Ai}(x_0);\mu_{Bj}(y_0);\mu_{Cij}(z)\} \\ &= \min\{\max_i \mu_{Ai}(x_0);\max_j \mu_{bj}(y_0);\mu_{Ci_0j_0}(z)\},\end{aligned} \tag{5}$$

where i_0j_0 is determined by $\mu_{Ai_0} = \max_i \mu_{Ai}(x_0)$ and $\mu_{Bj_0} = \max_j \mu_{Bj}(y_0)$. Hence, z_0 can be selected according to the maximum method:

$$\begin{aligned}\mu_{Ct}(z_0) &= \max_z \mu_{Ct}(z) \\ &= \max_z \max_{i,j} \min\{\mu_{Ai\times Bj}(x_0,y_0);\mu_{Cij}(z)\}\end{aligned}$$

$$= \max_{i,j}\max_{z} \min\{\mu_{Ai\times Bj}(x_0, y_0); \mu_{Cij}(z)\}$$

$$= \max_{i,j} \mu_{Ai\times Bj}(x_0, y_0)$$

$$= \mu_{Ai_0\times Bj_0}(x_0, y_0) = \min\{\mu_{Ai_0}(x_0); \mu_{Bj_0}(y_0)\}. \tag{6}$$

Once the input sets A_{i_0} and B_{j_0} are decided the output set $C_{i_0j_0}$ will work out corresponding to the rule i_0j_0. The inferred control action z_d will be determined at which

$$\mu_{i_0j_0}(z_d) = \max_{z}\mu_{Cij}(z), \tag{7}$$

when one of the following conditions is satisfied

a) $\max_{i} \mu_{Ai}(x_0) = 1, \max_{j} \mu_{Bj}(y_0) = 1$;

b) $\mu_{Ci_0j_0}(z)$ is symmetrical around its maximum.

Moreover, when $\max_{i,j} \mu_{Ai\times Bj}(x_0, y_0)$ is for several different i_0j_0, the final control action z_d will be the mean of the several corresponding maxima.

Hence we conclude that fuzzy logic PI controller can be considered as a two-dimensional multilevel relay[1].

3 Stability Analysis

An equivalent fuzzy PI control system of Fig. 1 is re-depicted as shown if Fig. 2. The following relations are satisfied according to the block diagram.

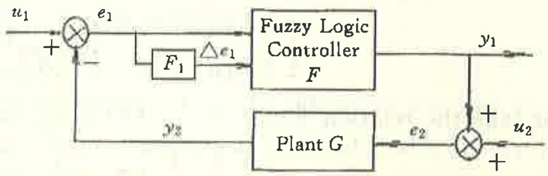


Fig. 2 Block diagram of an equivalent fuzzy PI control system 1

$$e_1 = u_1 - y_2, \tag{8}$$

$$e_2 = u_2 + y_1, \tag{9}$$

$$\Delta e = F_1 e_1, \tag{10}$$

$$y_1 = F\bar{e}(t), \quad \bar{e} = [e_1 \quad \Delta e_1]^T, \tag{11}$$

$$y_2 = Ge_2(t), \tag{12}$$

where F_1, F and G are corresponding maps. These equations can be written in a more compact form:

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \tag{13}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} F\bar{e}(t) \\ Ge_2(t) \end{bmatrix}. \tag{14}$$

Given inputs u_1, u_2 in L_p^1, and if F and G are causal and L_p-stable wb (without bias), taking norm in (14) and (13) gives

$$\begin{bmatrix} \| y_1 \| \\ \| y_2 \| \end{bmatrix} \leqslant \begin{bmatrix} \gamma_{1p} & 0 \\ 0 & \gamma_{2p} \end{bmatrix}\begin{bmatrix} \| \bar{e} \| \\ \| e_2 \| \end{bmatrix} \tag{15}$$

and

$$\begin{bmatrix} \| e_1 \| \\ \| e_2 \| \end{bmatrix} \leqslant \begin{bmatrix} \| u_1 \| \\ \| u_2 \| \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \| y_1 \| \\ \| y_2 \| \end{bmatrix} \leqslant \begin{bmatrix} \| u_1 \| \\ \| u_2 \| \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \gamma_{1p} & 0 \\ 0 & \gamma_{2p} \end{bmatrix}\begin{bmatrix} \| \bar{e} \| \\ \| e_2 \| \end{bmatrix}. \tag{16}$$

Notice that the norm of the increment $\| \Delta e_1 \| = \| e_1(n) - e_1(n-1) \|$ is bounded in a real system if the system is stable. Therefore there must exist a finite constant K such that $\|\Delta e_1\| \leqslant K' \|e_1(n)\|$ when $e_1(n) \neq 0$. Then we have:

$$\|\bar{e}\| = \sqrt{e_1^2 + (\Delta e_1)^2} \leqslant \sqrt{e_1^2 + (K'e_1)^2} = \sqrt{1 + K'^2}\|e_1\| = K\|e_1\|. \quad (17)$$

Substitute equation(17)into (16), the inequality becomes:

$$\begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix} \leqslant \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} K\gamma_{1p} & 0 \\ 0 & \gamma_{2p} \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix}. \quad (18)$$

Rearranging it as

$$\begin{bmatrix} 1 & -\gamma_{2p} \\ -K\gamma_{1p} & 1 \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix} \leqslant \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix}. \quad (19)$$

When $1 - K\gamma_{1p}\gamma_{2p} > 0$, we can get the solution of the inequality by left-multiplying the inverse of the coefficient matrix:

$$\begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix} \leqslant \frac{1}{1 - K\gamma_{1p}\gamma_{2p}} \begin{bmatrix} 1 & \gamma_{2p} \\ K\gamma_{1p} & 1 \end{bmatrix} \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix}. \quad (20)$$

When $e_1(n) = 0$, we can solve the inequality as the following form

$$\begin{bmatrix} \|e_1(n-1)\| \\ \|e_2(n)\| \end{bmatrix} \leqslant \frac{1}{K\gamma_{1p}\gamma_{2p}} \begin{bmatrix} 0 & \gamma_{2p} \\ K\gamma_{1p} & 1 \end{bmatrix} \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix}, \quad (21)$$

or take the relation $\|e_1\| = \|e_1(n)\| \leqslant \|e_1(n-1)\|$ into (21) and it holds:

$$\begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix} \leqslant \frac{1}{K\gamma_{1p}\gamma_{2p}} \begin{bmatrix} 0 & \gamma_{2p} \\ K\gamma_{1p} & 1 \end{bmatrix} \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix}. \quad (22)$$

However, it is obvious that if the inputs are limited in the L_p-space $u_i \in L_p$, for $i = 1, 2$, the errors $e_i \in L_p$ for $i = 1, 2$ hold. Finally, the outputs y_1 and y_2 have the solution forms

$$\begin{aligned} \begin{bmatrix} \|y_1\| \\ \|y_2\| \end{bmatrix} &\leqslant \begin{bmatrix} K\gamma_{1p} & 0 \\ 0 & \gamma_{2p} \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|e_2\| \end{bmatrix} \\ &\leqslant \frac{1}{1 - K\gamma_{1p}\gamma_{2p}} \begin{bmatrix} K\gamma_{1p} & 0 \\ 0 & \gamma_{2p} \end{bmatrix} \begin{bmatrix} 1 & \gamma_{2p} \\ K\gamma_{1p} & 1 \end{bmatrix} \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix} \\ &\leqslant \frac{1}{1 - K\gamma_{1p}\gamma_{2p}} \begin{bmatrix} K\gamma_{1p} & K\gamma_{1p}\gamma_{2p} \\ K\gamma_{1p}\gamma_{2p} & \gamma_{2p} \end{bmatrix} \begin{bmatrix} \|u_1\| \\ \|u_2\| \end{bmatrix}. \end{aligned} \quad (23)$$

This shows that the output y_1 and y_2 belong to the L_p-space. Therefore, the system is L_p-stable wb. We summarize this as a theorem below:

Theorem 1 For the Fuzzy PI(PD) control system of Fig. 1, it is L_p-stable wb if the following conditions are satisfied:

1) G is causal and L_p-stable wb,

2) $\gamma_{1p}\gamma_{2p} < \frac{1}{K}$,

with $\gamma_{1p} = \gamma_p(F)$ and $\gamma_{2p} = \gamma_p(G)$, the L_p-gain of fuzzy controller F and plant G respectively. K is a coefficient relying on the type of controller.

In the case of fuzzy PID control, similar conditions can be deduced with the different value of K and for the fuzzy P only $K = 1$ is needed to be selected.

As an application of the above theory, we improve it into another form in the region of complex plane.

Corollary Consider the Fuzzy PI(PD) control system of Fig. 1, where the plant is linear, time-invariant, and has the transfer function $\hat{g}(s) \in \hat{A}$ and the fuzzy controller belongs to the sector $[-r, r]$, then the system is L_2-stable wb provided

$$\sup_{\omega \in \mathbb{R}} |\hat{g}(j\omega)| < (K \cdot r)^{-1}.$$

The proof of it is simple and can be obtained directly from Theorem 1 with $p = 2$ and G_1: $x \to g^* x$.

The sufficient conditions are given in Theorem 1 and Corollary. However the conditions above seem too luxurious that in fact the fuzzy controller is often considered in half of the above sector. That is the sector of fuzzy controller is permitted to lie in the sector $[0, b]$. Therefore, the nonlinear function of controller output via error e_1 lies in the sector $[0, Kb]$. In this case the stability of fuzzy system can be discussed through reconstructing a system, as shown in Fig. 3, with the conditions: 1) k is a causal linear operator and L_p-stable wb; 2) $G(1 + kG)^{-1}$ is causal and L_p-stable wb. In accordance with the Loop Transformation Theorem[9], the original system is L_p-stable wb if $\gamma_p[G(1+kG)^{-1}]\gamma_p(KF-k)<1$. Now we select r and k as

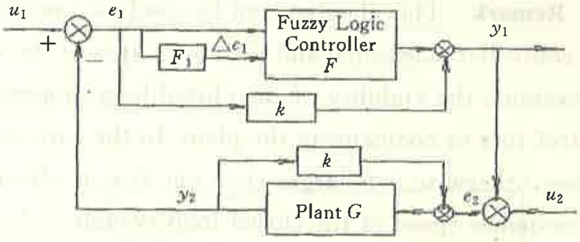


Fig. 3 Block diagram of an equivalent fuzzy PI control system 2

$$r = k = \frac{Kb}{2} = \frac{b'}{2},$$

then $b' = k + r$ and the map: $e_1 \to K f(t, e_1) - ke_1$ belongs to the sector $[-r, r]$. Now apply the Loop Transformation Theorem with $p = 2$ and the corollary above, since the map $KF - k$ belongs to the sector $[-r, r]$, its L_2-gain is at most r. Hence the original system is L_2-stable wb provided:

1) $$\hat{g}(s)(1 + k\hat{g}(s))^{-1} \in \hat{A},$$

2) $$\sup_{\omega} \left| \frac{\hat{g}(j\omega)}{1 + kg(j\omega)} \right| < r^{-1}.$$

Now let us consider

$$\sup_{\omega} \left| \frac{\hat{g}(j\omega)}{1 + k\hat{g}(j\omega)} \right| < r^{-1}.$$

This means

$$\left| \frac{X(\omega) + jY(\omega)}{1 + \frac{b}{2K}X(\omega) + j\frac{b}{2K}Y(\omega)} \right| < \frac{2}{b'}, \tag{24}$$

for all $\omega \in \mathbb{R}$. where X and Y denote the real part and the imaginary part of $\hat{g}(j\omega)$. Solving equation (24), there comes out the following condition:

$$X(\omega) = \mathrm{Re}(\hat{g}(j\omega)) > -\frac{1}{b'} = -\frac{1}{Kb}, \quad \text{for all} \quad \omega \in \mathbb{R}. \tag{25}$$

The above process can be summarized in a form of theorem as the stability conditions in the region of complex plane:

Theorem 2 The fuzzy control system of Fig. 1, with the fuzzy controller limited to the sector $[0,b]$, is L_2-stable wb if the following conditions hold:

1) $$\hat{g}(s) \in \hat{A};$$

2) $$\mathrm{Re}\hat{g}(j\omega) > -\frac{1}{Kb}, \quad \forall\, \omega \in \mathbb{R},$$

where K is a coefficient depending on the type of controller.

Remark This theorem can be used as a norm when designing a fuzzy controller. When the controller is selected and the upper limit of the sector b is known, we can apply the criterion examine the stability of the closed-loop system. If it is not stable we have to rectify the control rule or compensate the plant. In the case of fuzzy P control, the coefficient K is equal to one, otherwise it is larger than one that is effected by the structure of the controller and the response speed of the closed-loop system.

4 System Analysis and Simulation Result

In the simulations, the fuzzy controller is designed with two inputs, the error and the change of error, and one output, where input support sets X, Y and output universe of discourse Z are selected as $X = \{-5, -4, -3, -2, -1, -0, +0, 1, 2, 3, 4, 5\}$, $Y = \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\}$ and $Z = \{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$ respectively. Control rules are shown in Table 1. The fuzzy sets $A_1 \sim A_8(B_1 \sim B_7, C_1 \sim C_7)$ are successively described in the meaning of linguist values, as PB (positive big), PM (positive medium), PS (positive small), PZ (positive zero), NZ (negative zero), NS (negative small), NM (negative medium), NB (negative big). For any observed inputs that are first converted to fuzzy variables, the control rules (or the relation matrix) using the compositional rule of inference compute the control action and then reconvert it to the crisp value required to regulate the process. Fig. 4 (a) is a relation function of a controller between output and inputs when error and the change of error vary respectively in interval $[-10, 10]$ with step length 0.5 and the L_2-gain of the function is 1.9445. Fig. 4(b) is the relation function of another controller refined basing on the former control rules and the L_2-gain of the function is 1.5916. In the following analysis we will compare the process responses of different closed-loop systems affected by the different controllers.

Table 1 Control rules

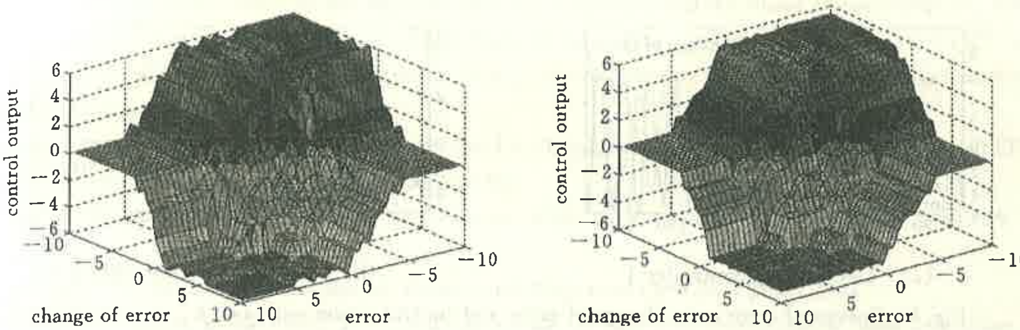
Change of error

Error	NB	NM	NS	Z	PS	PM	PB
NB			PB		PM	PS	Z
NM	PB			PM	PS		
NS		PM		PS		Z	NS
NZ	PM	PS		Z		NS	NM
PZ			Z		NS	NM	NB
PS	PS	Z		NS			
PM			NS	NM		NB	
PB	Z	NS	NM		NB		

Let us consider a plant with the following differential equation

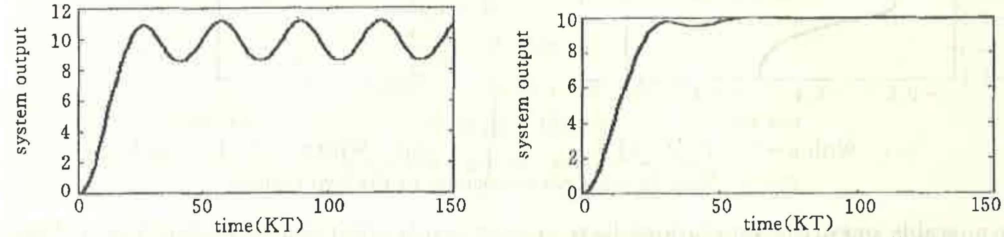
$$a_1 \frac{\mathrm{d}^3 y(t)}{\mathrm{d}t^3} + a_2 \frac{\mathrm{d}^2 y(t)}{\mathrm{d}t^2} + a_3 \frac{\mathrm{d}y(t)}{\mathrm{d}t} + a_4 y(t) = x(t). \tag{26}$$

For fuzzy logic control we take error between desired value $r(t)$ and the open-loop



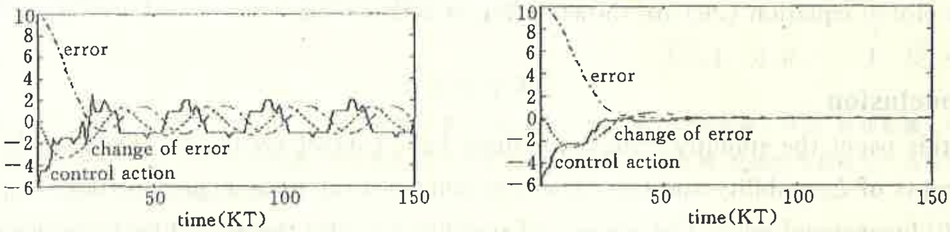
(a) For controller 1 (b) For controller 2

Fig. 4 The relation functions of controllers



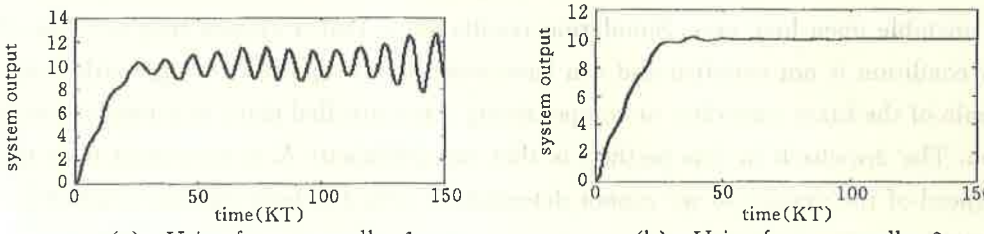
(a) Using fuzzy controller 1 (b) Using fuzzy controller 2

Fig. 5 Step responses of fuzzy control system with a=[1 1 2 0]



(a) Using fuzzy controller 1 (b) Using fuzzy controller 2

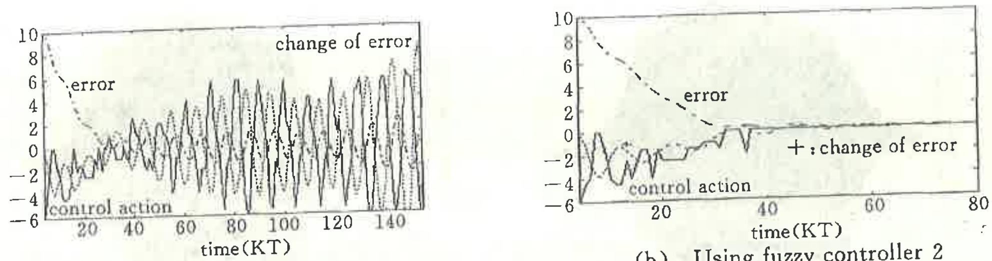
Fig. 6 Curves of error, the change of error and control action with a=[1 1 2 0]



(a) Using fuzzy controller 1 (b) Using fuzzy controller 2

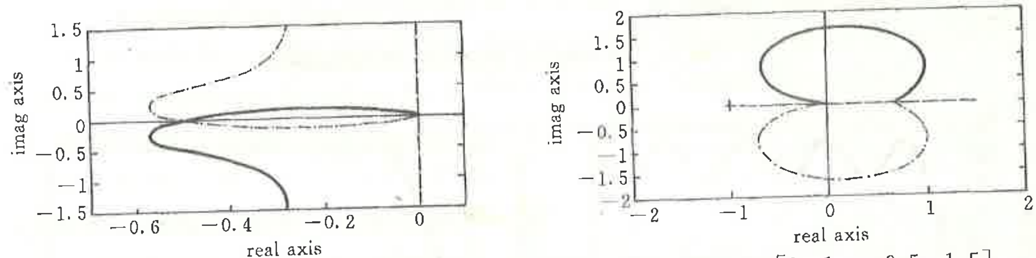
Fig. 7 Step responses of fuzzy control system with a=[0 1 −0.5 1.5]

system's output $y(t)$ and the change of error as inputs of fuzzy controller. The output of controller is the open-loop system's input. Step output responses of the closed-loop systems with fuzzy controller 1 and fuzzy controller 2 are give in Fig. 5, where the sample interval is 0.2s. The auxiliary curves showing the error, change of error and control action for the two different systems are given in Fig. 6 (a) and Fig. 6 (b). For different open-loop systems studied in-



(a) Using fuzzy controller 1 (b) Using fuzzy controller 2

Fig. 8 Curves of error, the change of error and control action with a=[0 1 −0.5 1.5]



(a) With a=[1 1 2 0] (b) With a=[0 1 −0.5 1.5]

Fig. 9 Nyquist plots corresponding to the two systems

cluding unstable ones, the simulations have similar results that can be seen in Fig. 7, Fig. 8. It is obvious from each pair of responses that the feedback system has been remarkably improved if the controller is suitably modified so that the stability condition is satisfied. The Nyquist plot of equation (26) are shown in Fig. 9 with $a = [a_1 \quad a_2 \quad a_3 \quad a_4] = [1 \quad 1 \quad 2 \quad 0]$ and $a = [0 \quad 1 \quad -0.5 \quad 1.5]$.

5 Conclusion

In this paper the stability criteria for fuzzy logic control system are discussed based on the concepts of L_2-stability and the circle criterion, with the fuzzy logic controller considered as a multidimensional relay. The analysis of stability provides theoretical basis for designing a fuzzy logic control system which is more proper than that of only depending on the experience of the operators. Responses of closed-loop systems are studied for different processes including unstable open-loop case. Simulation results show that a system may oscillate if the stability condition is not satisfied and can have preferable properties through either altering the L_2-gain of the fuzzy controller or compensating the controlled plant to satisfy the stability condition. The drawback in this method is that the cofficients K is concerned with the response speed of the system so we cannot determine it very precisely and the analysis is only approximate.

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模糊逻辑控制系统分析与设计

于德江

（香港理工大学机械工程系·香港）

毛宗源　周其节

（华南理工大学自动控制工程系·广州，510641）

摘要：本文把模糊逻辑控制器当作多维继电器，用 L_p 稳定性和园周判据分析闭环模糊逻辑控制系统的稳定性，给出闭环非线性系统与模糊逻辑控制器结合系统的稳定判据和设计方法. 并用计算机仿真试验，进一步将稳定判据应用到不同系统.

关键词：模糊逻辑控制；非线性系统；L_p 稳定性；园周判据

本文作者简介

于德江　1958 年生. 1982 年于吉林工业大学获学士学位，1987 年在华南理工大学获硕士学位. 曾在安徽工学院任教. 现在华南理工大学攻读博士学位. 研究兴趣：交流调速，自适应控制，神经网络，人工智能，电动汽车及电子产品设计.

毛宗源　见本刊 1998 年第 1 期第 151 页.

周其节　见本刊 1998 年第 1 期第 38 页.