Study on the Structure and Algorithm of a Feedback Fuzzy Controller

QU Sheng-li and QIAN Bo
School of Mechano-Electronic Engineering
Xidian Univ.
Xi'an 710071, China
slqu@mail.xidian.edu.cn

ZHU Xin-zhi and XU Wen-long
School of Mechano-Electronic Engineering
Xidian Univ.
Xi'an 710071, China
zhuxzhi@hotmail.com

***Abstract*--This paper presents the structure and algorithm of a new fuzzy logic controller which contains a feedback of control action in its input and therefore is called dynamic fuzzy controller, mainly studies the first-order dynamic fuzzy controller and six new corresponding fuzzy inference rules are given. The results show that the performances of the control systems with the first-order dynamic fuzzy logic controller, especially the robustness of resisting uncertainty and anti-time-delay, are much better than those with the traditional static fuzzy controller which has two inputs and forty nine fuzzy inference rules.**

Keywords—fuzzy control; feedback fuzzy controller; dynamic fuzzy controller

I. INTRODUCTION

The theory of fuzzy set has been in developing for 30 years since it was presented by Zedeh in 1965, and one of its most important application fields is in control engineering [1,2,3,4]. Generally speaking, fuzzy logic controller will be an effective way in designing a control system when controlled processes are too difficult to be described by physical or chemical principles, or its models are too complicated to be solved. The design of a fuzzy controller does not depend on the analysis and synthesis of process mathematical model, but all of its control rules come from the expert's knowledge or the operator's experiences [3,4,5], and therefore fuzzy logic controller is not dynamic in generally [4]. We can also know that fuzzy logic controller is a static controller from that fuzzy controller is equivalent to a multi-value relay in stability analysis [3].

To remedy this disadvantage of fuzzy logic controller, the three followed methods are developed in traditional fuzzy control theory. The first one is a fuzzy logic controller with adjustable parameters [6,7,8], to say, the fuzzy PID method which unifies the PID parameters and then adjust them by fuzzy inference rules. In this case, the fuzzy logic system still remains static. The second method is the Takagi-Sugeno method which is based on fuzzy-neural adaptive method to change the proportional factors in T-S fuzzy system [9,10]. In this case, the fuzzy logic system is also static in a relative short time. The third method is the fuzzy dynamic model which is based on T-S model to obtain the entire dynamic model of the system by weighting several local linear dynamic model [11] and applied to several situations [12]. In this case, the fuzzy logic system itself is still static.

In classical and modern control theories, controllers generally are dynamic, or state-feed backed. Man, as a controller, is also dynamic since he or she takes into account of the previous control operation and error.

From the above, it's necessary to study dynamic fuzzy logic controllers and its structures. The authors present a structure of dynamic fuzzy logic controllers, mainly study the first-order dynamic fuzzy logic controller, and compare it with traditional static fuzzy logic controller which has two inputs and forty nine fuzzy inference rules. The results show that the performances of the control systems with the first-order dynamic fuzzy controller are much better than that with the traditional static fuzzy controller.

II. THE STRUCTURE OF A NEW DYNAMIC FUZZY CONTROLLER

The authors study the dynamic fuzzy controller and present a structure-simple dynamic fuzzy controller (DFLC). Figure 1 shows the structure of the nth-order DFLC.

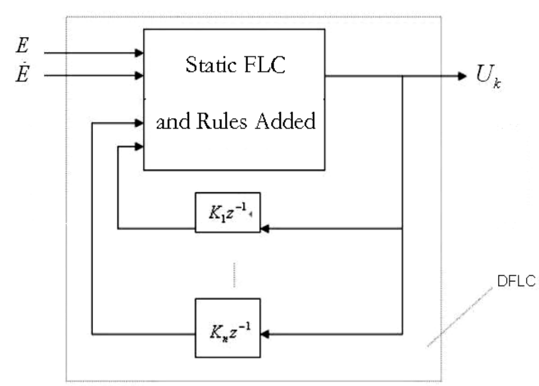


Figure 1 the structure of the nth-order DFLC

The output of DFLC is:

$$U_k = f(U_{k-1}, U_{k-2}, \cdots, U_{k-n}, E_k, \dot{E}_k) \quad (1)$$

Where $U_k, U_{k-1}, U_{k-2}, \cdots, U_{k-n}$ are the outputs of DFLC on discrete time, $E_k, \dot{E}_k$ are the input error and its differential at time $t = t_k$, z^{-1} is first-order delay factor, and $K_1, \cdots, K_n$ are parameters, respectively.

The structure of the simplest first-order DFLC is shown in Figure 2.

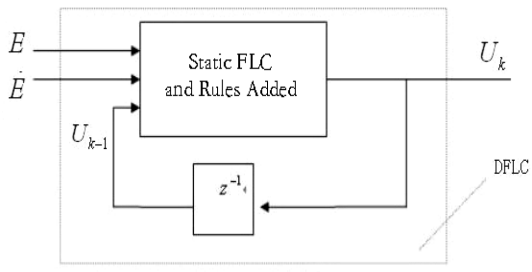


Figure 2 the structure of first-order DFLC

III. THE FUZZY INFERENCE RULES OF THE FIRST-ORDER DFLC

A. Static Part of the First-order DFLC

It's all the same with the traditional static fuzzy logic controller which has two inputs with E_k and $\dot{E}_k$, and has forty nine fuzzy inference rules. The rules are formed like this:

$$IF(E_k, \dot{E}_k) \qquad THEN \qquad (U_k)$$

B. Dynamic Part of the First-order DFLC

Traditional fuzzy control systems will work well if the Input and output (I—O) of a controlled process satisfy the monotonic relation. This is the point. Accordingly, the traditional fuzzy control algorithms are also monotonic. [13]

Let the input and output of a controlled process are U_k and Y_k, respectively. Because the traditional fuzzy controllers (FLC) are static, so they do not take into account of the effect of $U_{k-1}, U_{k-2}, \cdots, U_{k-m}$ on Y_k. When the dynamic characteristic of a controlled process is complicated, the relation between its input and output will not be monotonic.

Therefore, in the added rules of the first-order DFLC, U_k should be generated by $\dot{E}_k$ and U_{k-1}. According to the monotonic relation, the control systems should satisfy the following relations:

IF U_{k-1} >0，THEN $\dot{E}_k$ >0

IF U_{k-1} <0，THEN $\dot{E}_k$ <0

If the above two relations are not satisfied, it shows that the static fuzzy controller SFLC is unable to compensate the dynamic characteristic of the controlled process and the system will oscillate. Therefore, in the first-order dynamic fuzzy controller, at least two fuzzy rules should be added as follow:

IF U_{k-1} >0 AND $\dot{E}_k$ <0 THEN U_k <0

IF U_{k-1} <0 AND $\dot{E}_k$ >0 THEN U_k >0

To be slightly detailed, the number of the added rules in the first-order dynamic fuzzy controller DFLC will be six as follow:

IF U_{k-1} IS N *AND* $\dot{E}_k$ IS *PS* THEN U_k IS PS

IF U_{k-1} IS N AND $\dot{E}_k$ IS PM THEN U_k IS PM

IF U_{k-1} IS N AND $\dot{E}_k$ IS PB THEN U_k IS *PB*

IF U_{k-1} IS P *AND* $\dot{E}_k$ IS NS THEN U_k IS NS

IF U_{k-1} IS P AND $\dot{E}_k$ IS NM THEN U_k IS NM

IF U_{k-1} IS P AND $\dot{E}_k$ IS NB THEN U_k IS NB

These added fuzzy inference rules should be able to reduce system oscillation, therefore make the system transient response quick and promote system's stability.

IV. THE COMPARISON BETWEEN DFLC AND SFLC BY SIMULATION

The controlled process, the forty nine fuzzy inference rules and their membership functions of SFLC are all come from the literature [3] pp.277-282. The transfer function of the controlled process is as follow:

$$G_p(s) = \frac{20e^{-\tau s}}{(2s+1)(4s+1)(2.2s+1)} \quad (2)$$

Based on the SFLC in the literature [3], the feedback U_{k-1} is added onto the input of the first-order fuzzy controller, and the six fuzzy inference rules presented in section III are also added to the rules of SFLC. In this way, the first-order fuzzy controller is constructed (shown in figure 2). The system is simulated with the Fuzzy Toolbox and Simulink in Matlab.

Referred to the literature [3], the universe of discourse of the input and output variables in DFLC are defined as : $E \in [-6,6]$, $\dot{E} \in [-1,1]$, $U \in [-7,7]$, $U_d \in [-7,7]$, where U_d is the feedback variable U_{k-1} in DFLC as shown in figure 2. The reference input signal of the closed loop control system is a step signal with the amplitude 1.5.

A. The Comparison between DFLC and SFLC with the Variation of Parameters in the Controlled Process

The transfer function of the controlled process is shown in equation (2), its transfer coefficient K is set to be 20, 100, 1000 and 2000 respectively, and its delay time τ is set to be 0. The simulation results are as follows:

- With the increase of transfer coefficient K , the dynamic performances of the control system with the first-order DFLC are obviously better than those with SFLC. Taken K =1000 as an example, figure 3 shows the step responses of the closed loop system with the first-order DFLC and SFLC.
- The first-order DFLC performs better than SFLC in the high frequency oscillation. When K is very big, the operation condition of system become worse and the oscillation is obvious. In figure 3 it is shown that the six added rules in the first-order DFLC are able to reduce the oscillation obviously.

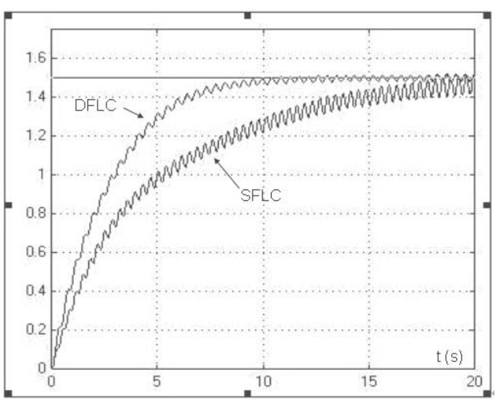


Figure 3 the step responses of the closed loop system with $K = 1000$ and $\tau = 0$

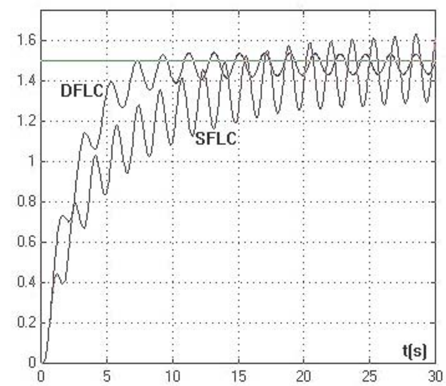
With the time constants of the controlled process changed from 0.1 to 10 times and K from 1 to 100 times, simulation results also indicate that the performances of the control system with the first-order DFLC are obviously better than those with SFLC.

B. The Comparison between DFLC and SFLC with the time delay

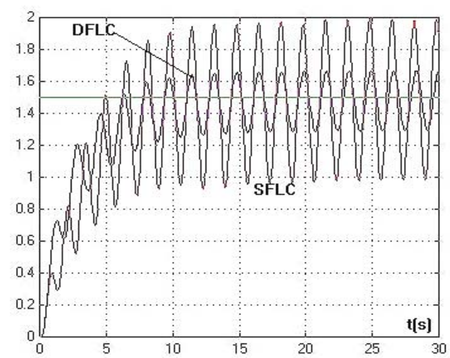
The transfer function of a controlled process is shown in equation (2), its K and time delay factor τ are taken as （20，0.05），（50，0.05）, (100，0.05), （20，0.5）, respectively. In the above situation, the simulation results are as follows:

- Both the first-order DFLC and SFLC are sensitive to the change of time delay factor τ .
- The first-order DFLC performs better than what SFLC does in against time delay.

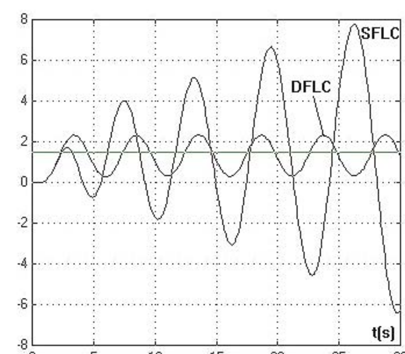
From the figure 4 bellow, it is can be seen that the 6 rules added to the first-order DFLC can obviously alleviate the effect of time delay.



(a)



(b)



(c)

Figure 4 the step responses of the closed loop system with time delay.
（a） K=50， $\tau = 0.05$； (b) K=100， $\tau = 0.05$； (c) K=20， $\tau = 0.5$。

C. The Comparison between DFLC and SFLC with the Change in the Universe of Discourse of Their Input Variables

Let the universe of discourse of the input variables changes from 0.1 to 1 times, for example, $E \in [-0.6, 0.6]$, $\dot{E} \in [-0.1, 0.1]$, $U \in [-7, 7]$, $U_d \in [-7, 7]$。The simulation results are as follows:

- If the universe of discourse of the input variables is set very small, the SFLC is sensitive to the changes of K and τ .
- If the universe of discourse of the input variables is set very small, the performance of the first-order DFLC is much better than that of the SFLC.

From the figure 5, it is can be seen that the 6 rules added to the first-order DFLC can obviously adapt to the changes of the universe of discourse of the input variables, and alleviate the effect of time delay.

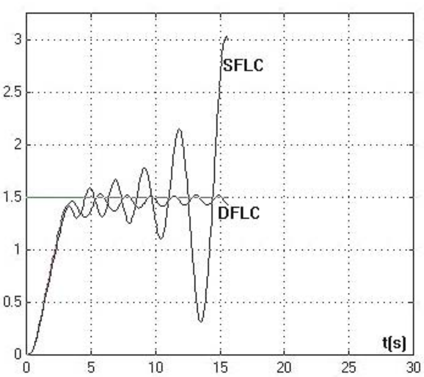


Figure 5 the step responses of the closed loop system with the universe of discourse of E 、 $\dot{E}$ changed to 0.1 times, and $\tau = 0.05$

D. The Analysis of the Simulation Stability

To compare the control system robust stability of the first-order DFLC with SFLC, the fourth-order Runge-Kutto method of fixed step length is used to look for the universe of discourse of the input variable E and $\dot{E}$ that make the result of the simulation dispersed easily. Searched by simulation, the universe of discourse of the input variable E and $\dot{E}$ that make the simulation dispersed easily is： $E \in [-0.6, 0.6]$, $\dot{E} \in [-0.03, 0.03]$, $U \in [-7, 7]$, $U_d \in [-7, 7]$ 。 The simulation results are as follows:

- The simulation errors become larger as the simulation step length becomes longer. When the controlled process described by formula (2) takes the K =100, and the simulation step length h =0.04, the closed loop control system of the first-order DFLC is stable and that of SFLC is unstable. See figure 6.
- The simulation errors are equivalent to the noises added in system, so the robust stability of the first-order DFLC is much better than that of the SFLC.

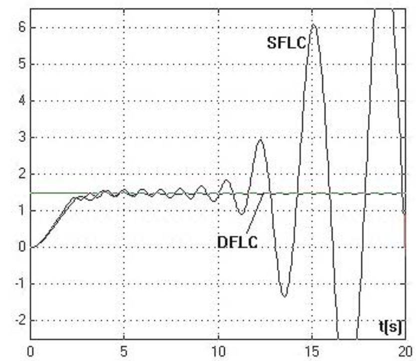


Figure 6 the step responses of the closed loop system with K =100 and h =0.04

V. Conclusions

This paper presents a structure of dynamic fuzzy logic controllers, studies the first-order dynamic fuzzy logic controller, and compares it with traditional static fuzzy logic controller which has two inputs and forty nine fuzzy inference rules. The results show that the performances of the control systems with the first-order dynamic fuzzy controller are much better than that with the traditional static fuzzy controller. The major advantages of the first-order DFLC are concluded as follow:

- With stronger abilities to resist both the internal uncertainty (the changes of system parameters) and also the external uncertainty (disturbances).
- With stronger abilities to resist the effect of time delay.
- With stronger abilities to resist the changes of the fuzzy controller parameters itself, such as the changes of the universe of discourse of the input variables.
- With better dynamic performances in closed system.

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