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Fuzzy Proportional-Derivative Controller with Adaptive Control Resolution

○Seok-Yong Oh* Dong-Jo Park*
* Department of Electrical Engineering, Korea Institute of Science & Technology (KAIST)
373-1 Kusong-dong, Yusong-gu, Taejon, Republic of Korea
Tel : +82-42-869-3438; Fax : +82-42-869-3410; E-mail : syoh@falcon.kaist.ac.kr

Abstracts A new design method is proposed for a fuzzy PD controller. By analyzing phase plane characteristics we can build and optimize the rule base of fuzzy logic controller. Also, a new gain tuning method is used to improve performance in the transient and steady state. The improved performance of the new methodology is shown by an application to the design of control system with a highly nonlinear actuator.

Keywords PD Control, Resolution, Tuning, Nonlinear Control, Phase Plane

1. Introduction

The fuzzy logic controller(FLC) design can be divided into two major parts : the knowledge base design and the gain tuning. Although there have been several papers about these design methodologies[1][2], actually there is yet no systematic procedure for the design of the knowledge base and tuning of gain. The control rules are usually determined heuristically by the experiments of an expert in most cases[3][4].

The phase plane characteristics can be used as a guidance for building and optimizing the rule base[5]. The scaling gains are related to the control variables of the FLC to form fuzzy PD control. They map physically measured data into predetermined universe of discourse(UOD) which gives the measurement range that these variables can take. By varying the range of UOD we can make the control variable, which is related to that UOD, coarse or fine. Moreover, simultaneous tuning of scaling gain can achieve good performance in both the transient and steady state.

In this paper according to the above points, a new method of designing the control rule base and the gain tuning is presented. Through an application of the new method to designing control systems which have nonlinear actuators, we show that the new method gives good performance even under strongly nonlinear environments.

2. Fuzzy Logic Control

2.1 Knowledge Base Design

The knowledge base of an FLC is composed of two components, the data base and the fuzzy control rule base.

2.1.1 Data Base Design

The data base of an FLC is concerned with control variables, membership functions. At first, the control variables should be defined. The control input variables for the FLC are usually chosen as error and change of error. The control output variable is defined as the output for a fuzzy PD control.

In the transient state and steady state, each region needs different control resolution. Control resolution depends on the fuzziness of the control variables and the fuzziness of the control variable mainly depends on the fuzziness of MFs of its labels. As the result, different control resolution means different fuzziness of membership functions(MFs) of its labels. In the transient state, because of relatively large error, coarse variables are desirable. And conversely in the steady state fine variables are needed. Therefore the fuzziness of MFs of each control input variable should be changed according to the change of states.

We can adjust the fuzziness of the control input variable, namely, the control resolution by varying the range of universe of discourse of each variable. This is shown in Fig 1. This modification

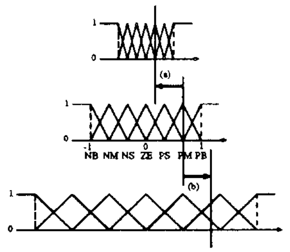


Fig. 1: Variable UOD

of UOD of the input variable is executed on-line by the following nonlinear function of input variables.

$$f_1(e, \Delta e) = 1 - e^{-\gamma\sqrt{\alpha e^2 + \beta \Delta e^2}} \quad (1)$$

where α and β are weighting constants for each variable and γ is a design constant. If the initial range of UOD is $[-A, A]$, during the control process it becomes $[-f_1 A, f_1 A]$.

The control output can be determined from the method of the center of gravity in (2)

$$F[e(k), \Delta e(k)] = C_u \frac{\sum_i^m w_i y_i}{\sum_i^m y_i} \quad (2)$$

where C_u is the output control gain, w_i is the grade of the i^{th} output MF, y_i is the output label for the value contributed by the i^{th} MF and m is the number of contributions from the rules.

2.1.2 Design of Control Rule Base

Now we introduce a rule optimization technique based on the analysis of phase plane characteristics. The general step response of a stable closed loop system is shown in Fig. 2. In Fig. 2(b) each region $B_1, B_2, B_3, B_4, c_1, c_2, d_1$ and d_2 corresponds to each region in Fig. 2(a). When $e = 0$, control outputs in the vertical region are determined as the same sign and magnitude as Δe. When $\Delta e = 0$, control outputs in the horizontal region are determined as the same sign and magnitude as e.

Fig. 3(a) shows the map of a rule table for this process control. In the region B1, error is relatively large and rules for shortening the rise time are needed. As the state goes to the point c1, rules for preventing overshoot are required. So the rules for the control output in this region are positive. In the region B2, rules for minimizing the overshoot are needed.

The control outputs near $e = 0$ are positive because Δe is positive and control outputs near

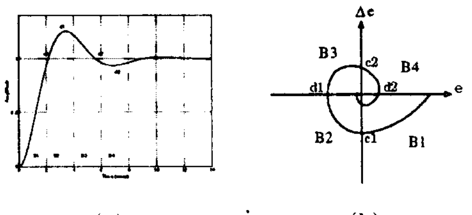


Fig. 2: General Step Response and Phase Plane Characteristics

Δe=0 are negative because e is negative. Fig. 3(b) describes the rule table obtained finally.

2.2 Gain Tuning

Normally, it is difficult to maintain great performance in both the transient and steady state because different control resolutions are required for each region as stated above. Let us think about the points c1 and c2 in Fig. 2(b). At the point c1 ($e = 0$), due to an excessive amount of control output, overshoot is about to take place. So the magnitude of control output should be reduced near this point.

By the same reasoning at the point c2, for preventing undershoot, we should reduce the gain of control output. From this point of view, to obtain the desired control resolution we should adjust the control output gain during the control process. We do this by (3) which represents a function of e.

$$f_2(e) = \sqrt{1 - e^{-\gamma|e|}} \quad (3)$$

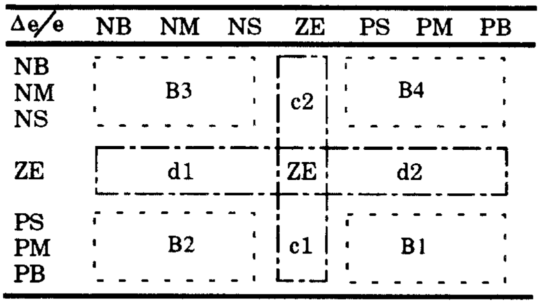
If the scaling gain of the output is C_u, its variable form is as follows:

$$C_u(k) = f_2(e(k))C_u(0) \quad (4)$$

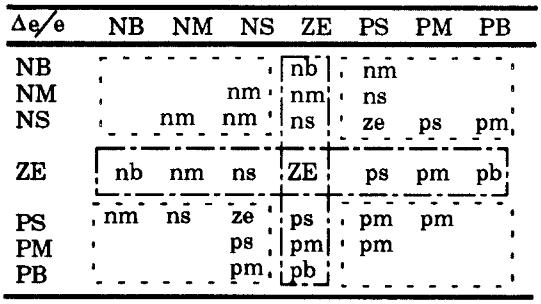
where $C_u(0)$ is an initial value of the scaling gain.

3. Applications

In order to verify advantages of this fuzzy control scheme, it has been applied to a second order system with dead zone and hysteresis characteristics in an actuator. The system used in the simulation was $\frac{1}{s(s+1)}$. The block diagram of this system is shown in Fig. 4. The parameter values are $C_e = 1.0$, $C_{\Delta e} = 0.094$, $C_u(0) = 3.0$,



(a)



(b)

Fig. 3: Map of Rule Table and Extracted Control Rules

$\alpha = \beta = \gamma = 1.0$, And Fig. 5 shows the simulation results of the proposed scheme comparing performance with that of a conventional fuzzy PD controller. For Fig. 5(a)(b), $U_d = 0.5$, $U_s = 1.0$, $U_m = 1.0$, $Km = 1.0$. were used and for Fig. 5(c)(d), $U_d = 0.5$, $U_s = 1.5$, $U_m = 1.0$, $Km = 1.0$.

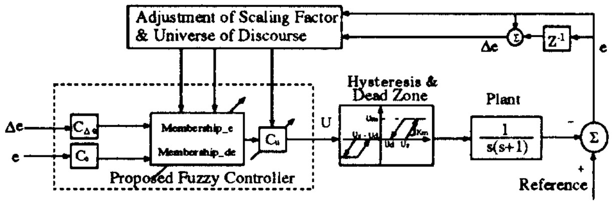
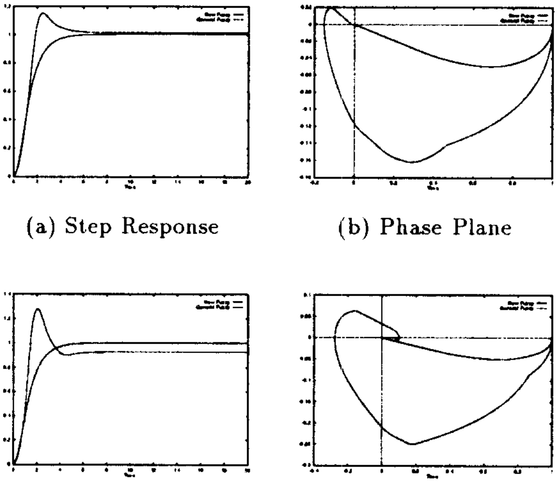


Fig. 4: Proposed FLC with Dead Zone and Saturation in Actuator

4. Conclusions

We showed that the phase plane is very useful for designing of the control rule base of a fuzzy logic controller. Based on the fact that different control resolutions are required in the transient and steady state respectively, we updated the range of universe of discourse of control input variables so that it could reflect the variation of each input variable.

For fast convergence and good performance, the scaling gain of output variable is tuned during the control process. Application of this method to a system with dead zone and hysteresis characteristics in the actuator showed better performance than the conventional fuzzy PD control method.



(a) Step Response (b) Phase Plane

(c) Step Response (d) Phase Plane

Fig. 5: Comparison of Simulation Results

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