A Suggestion of Nonlinear Fuzzy PID Controller to Improve Transient Responses of Nonlinear or Uncertain Systems

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Abstract

In order to control systems which contain nonlinearities or uncertainties, control strategies must deal with the effects of them. Since most of control methods based on system mathematical models have been mainly developed focused on stability robustness against nonlinearities or uncertainties under the assumption that controlled systems are linear time invariant, they have certain amount of limitations to smartly improve the transient responses of systems disturbed by nonlinearities or uncertainties.

In this paper, a nonlinear fuzzy PID control method is suggested which can stably improve the transient responses of systems disturbed by nonlinearities, as well as systems whose mathematical characteristics are not perfectly known. Although the derivation process is based on the design process similar to general fuzzy logic controller, resultant control law has analytical forms with time varying PID gains rather than linguistic forms, so that implementation using common-used versatile microprocessors can be achieved easily and effectively in real-time control aspect.

Keywords: fuzzy control rules, fuzzification, defuzzification, fuzzy PID control, fuzzy logic controller(FLC)

I. Introduction

As industry has been developed day by day, the demand for control system design has been changing in direction of accomplishing more accurate and fast control by improvement of transient responses. In order to satisfy this requirements, the effects of modeling errors or uncertainties must be considered, being accompanied in the process of mathematical modeling for the controlled plant or process.

During the past several years, fuzzy control has emerged as one of the most active and important branch of fuzzy set theory since the invention of the first fuzzy controller using Zadeh's fuzzy logic by Mamdani[1] in 1974. Since a large number of literature on fuzzy control and application in industrial processes have been growing rapidly, it is difficult to make a comprehensive survey, so that the references[2, 3] are addressed for survey.

Fuzzy logic controller(FLC) is based on the fuzzy logic which is much closer in spirit to human thinking and natural language than the traditional logical system. Viewed in this perspective, the essential part of the FLC is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference. Then, in essence, the FLC provides an algorithm which can convert

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the linguistic control strategy based on expert knowledge into an automatic control strategy. In this point of view, the methodology of the FLC appears particularly useful in case the processes are too complex for analysis by conventional control techniques, and in case the available source of information are regarded inexactly or uncertainly. However, at present there is few literature on the systematic procedure for the design of an FLC purely besides works by M. Sugeno et al.[4-6] The trends are appeared in direction of designing an FLC systematically and assuring stability with the aid of conventional control theories, such as sliding mode control[7] and PI control.[8-10]

In this paper, a nonlinear fuzzy PID control law may be derived by developing fuzzy PI control suggested by H. Ying et. al.,[8, 9] in order to control systems which contain nonlinearities or uncertainties. Although the derivation is based on the design process of general FLC, resultant control law has analytical forms with time varying gains rather than linguistic forms. And computer simulations are accomplished to evaluate the transient performance of suggested method through the comparison of its responses with those of nonlinear fuzzy PI suggested in [9], by employing several example systems.

Ⅱ. Derivation of nonlinear fuzzy PID control law

The blockdiagram of the FLC suggested in this paper is described by Fig. 1.

Although most popular fuzzy controller developed so far employ two inputs, such as error and rate of change of error(rate for short) about a setpoint, an additional input named as accelerated rate of change of error(acc for short) is used for FLC. With these three inputs, the structure of the FLC can be composed of two independent parallel fuzzy control blocks which contain fuzzy control rules and defuzzifier respectively.

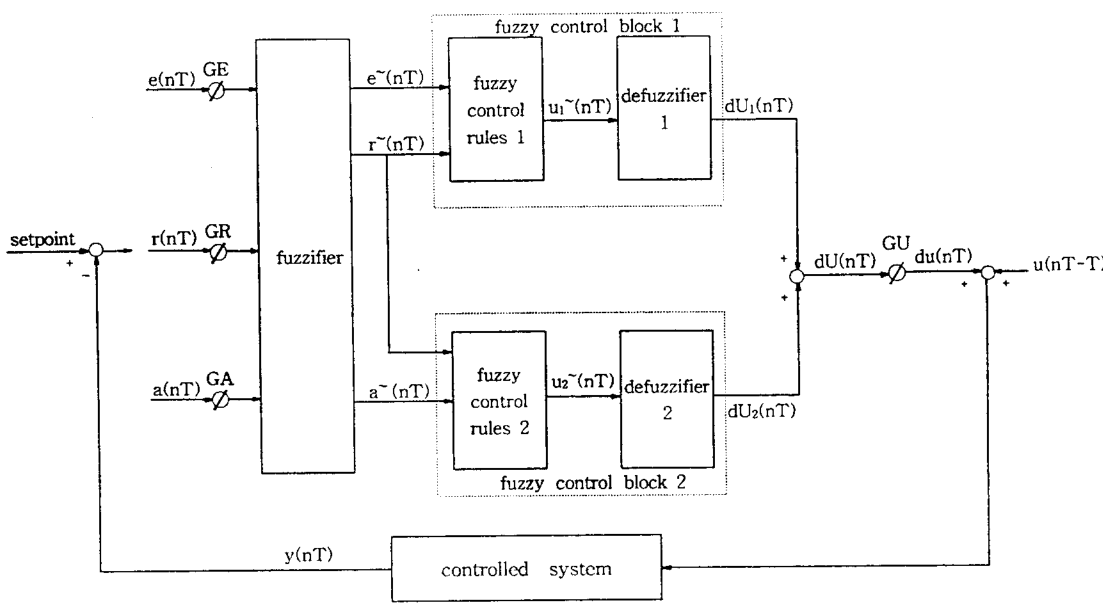

Fig 1. The structure of FLC suggested in this paper

Then the incremental output of the FLC is formed by algebraically adding the two outputs of fuzzy control blocks.

Here we employ the following notations:

$$e(nT) = setpoint - y(nT)$$
$$\tilde{e}(nT) = F(e^*),\ e^* = GE*e(nT)$$
$$r(nT) = [e(nT) - e(nT - T)]/T$$
$$\tilde{r}(nT) = F(r^*),\ r^* = GR*r(nT)$$
$$a(nT) = [r(nT) - r(nT - T)]/T$$
$$= [e(nT) - 2e(nT - T) + e(nT - 2T)]/T^2$$
$$\tilde{a}(nT) = F(a^*),\ a^* = GA*a(nT)$$
$$u(nT) = du(nT) + u(nT - T),\ du(nT) = GU*dU(nT)$$
$$dU(nT) = dU_1(nT) + dU_2(nT)$$

where n is positive integer and T is sampling period.

The y(nT), e(nT), r(nT) and a(nT) denote process output, error, rate and acc at sampling time nT, respectively.

GE(gain for error) is the input scaler for error, GR(gain for rate) is the input scaler for rate, GA(gain for acc) is the input scaler for acc and GU(gain for controller output) is the output scaler of the FLC. F(.) means fuzzification of the scaled input signal(.). The dU(nT) denotes the incremental output of the FLC at sampling time nT. The $dU_i(nT)$ (i=1,2) designates the incremental output of the fuzzy control block i from defuzzification of the fuzzy set "output i" $\tilde{u}_i(nT)$ at sampling time nT.

Thus the components of an FLC contained in this paper include:

1) input scalers GE, GR, GA and output scaler GU
2) a fuzzification algorithms for scaled error e^*, scaled rate r^*, scaled acc a^* and output of each control block
3) fuzzy control rules for each control block
4) fuzzy decisionmaking logics to evaluate the fuzzy control rules for each control block
5) a defuzzification algorithm to obtain crisp output of each control block for the control of process.

2.1 Fuzzification algorithm for scaled inputs

The fuzzification algorithm for scaled inputs is shown in Fig. 2.

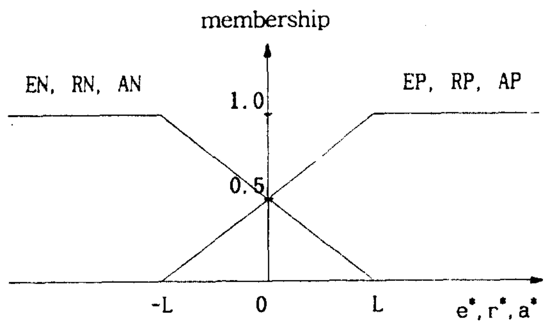

Fig 2. Fuzzification algorithm for the inputs of FLC e^*, r^* and a^*

The fuzzy set "error" has two members EP(error_positive) and EN(error_negative); the fuzzy set "rate" has two members RP(rate_positive) and RN(rate_negative); the fuzzy set "acc" also has two members AP (acc_positive) and AN(acc_negative). The fuzzy set "output1" has three members OP(output_positive), OZ(output_zero) and ON(output_negative) shown as Fig. 3 for the fuzzification of incremental output of fuzzy control block 1.

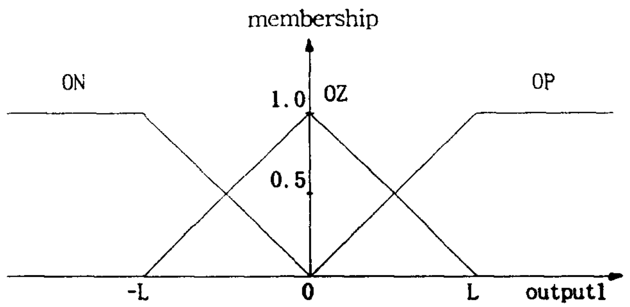

Fig 3. Fuzzification algorithm for the incremental output of fuzzy control block 1 in FLC

The fuzzy set "output2" has two members OPM(output_positive_middle) and ONM(output_negative _middle) as shown in Fig. 4 for the fuzzification of incremental output of fuzzy block 2.

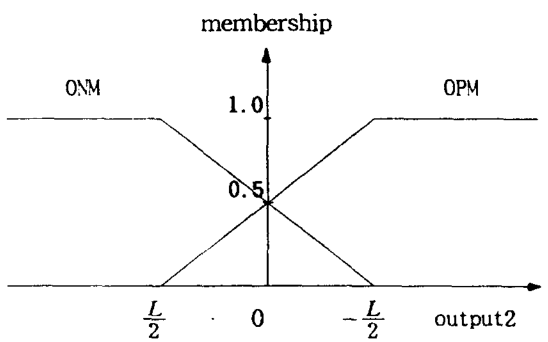

Fig 4. Fuzzification algorithm for the incremental output of fuzzy control block 2.

Although the grades of membership function of the output members may be decided from the fuzzy control rules, the definitions of fuzzy set "output1" and "output2" are necessary for the fuzzification and fuzzy control rules. It should be noted that the fuzzification algorithm of the fuzzy set "output2" be different from that of the "output1", because fuzzy control block 2 has characteristics to compensate the behavior of fuzzy control block 1.

2.2 Fuzzy control rules and fuzzy logics for evaluation of the fuzzy control rules

Fuzzy control rules must be made based on expert experience and control engineering knowledge, or based on operator's control action. In this paper, fuzzy control rules were made based on expert experience and control engineering knowledge, and each control rule set was composed of four linear fuzzy control rules for each fuzzy control block.

For fuzzy control block 1, four linear fuzzy control rules are given as;

$(R1)_1$: if error = EP and rate = RP then output = OP
$(R2)_1$: if error = EP and rate = RN then output = OZ
$(R3)_1$: if error = EN and rate = RP then output = OZ
$(R4)_1$: if error = EN and rate = RN then output = ON

For fuzzy control block 2, four linear fuzzy control rules, different from that of fuzzy control block 1, are given as;

$(R1)_2$: if rate = RP and acc = AP then output = OPM
$(R2)_2$: if rate = RP and acc = AN then output = ONM
$(R3)_2$: if rate = RN and acc = AP then output = OPM
$(R4)_2$: if rate = RN and acc = AN then output = ONM

We, then now, apply fuzzy control logic to evaluate each fuzzy control rules. The fuzzy logics with which we are concerned are those of Zadeh and Lukasiewicz. In evaluating the control rules, it is proper to use the Zadeh AND logic to evaluate the individual control rules, but the Lukasiewicz OR to evaluate the implied OR between control rules $(R2)_1$ and $(R3)_1$ in control block 1.

The control rules $(R1)_1$-$(R4)_1$ and $(R1)_2$-$(R4)_2$ all employ the Zadeh AND of two conditions in the antecedents, such as one on the scaled rate, and the other on the scaled error. Since the Zadeh AND is the minimum of two values, two different conditions arise for each rule in fuzzy control blocks, that is,

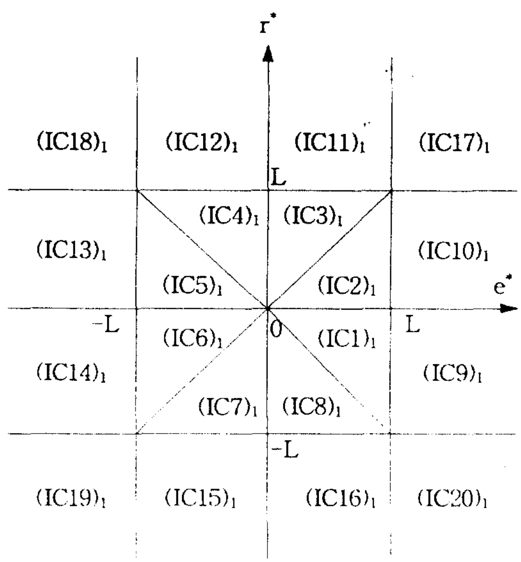

Fig 5. Possible input combinations of e* and r* for control block 1.

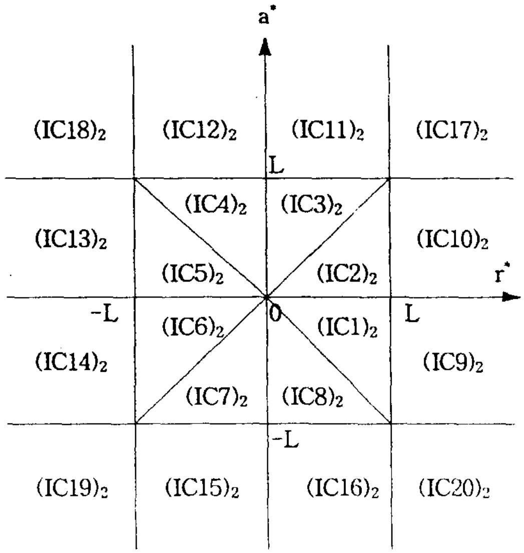

Fig 6. Possible input combinations of r* and a* for control block 2.

one when the scaled error is less than the scaled rate and one when the scaled rate is less than the scaled error in control block 1. In the similar manner, two conditions also arises between scaled rate and scaled acc in control block 2.

The eight different combinations of scaled error and scaled rate constituting inputs to the control rules are shown graphically in Fig. 5 for the control block 1.

For the control block 2, the eight different combinations of scaled rate and scaled acc are shown in Fig. 6.

These combinations of inputs must be considered when the fuzzy controller rules are evaluated. The results of evaluating the fuzzy control rules $(R1)_1$-$(R4)_1$ when scaled error and rate are in [-L, L], are given in Table 1.

In Table 1, μ_{EP} and μ_{EN}(μ_{RP} and μ_{RN}) mean the membership values of EP and EN(RP and RN) in the fuzzy set "error"("rate").

For example, when the values of scaled error e* and rate r* are given, let the membership values obtained by using the fuzzification algorithm shown in Fig. 2, be given as μ_{EP} and μ_{RP}. Then, say in rule $(R1)_1$, the membership value associated with the member, ON, of the fuzzy set "output1" is the Min(μ_{EP}, μ_{RP}). In this way, the membership values listed in Table 1. Notice that

$$\mu_{EP}=[r^{*}+L]/2L=[GE*e(nT)+L]/2L \quad (1)$$

$$\mu_{EN}=[L-GE*e(nT)]/2L \quad (2)$$

$$\mu_{RP}=[GR*r(nT)+L]/2L \quad (3)$$

$$\mu_{RN}=[L-GR*r(nT)]/2L \quad (4)$$

$$\mu_{EP}+\mu_{EN}=1 \quad (5)$$

$$\mu_{RP}+\mu_{RN}=1 \quad (6)$$

Also, be aware that in our case the Lukasiewicz OR reduces to the sum of the grades of membership being ORd, since this sum can never be greater than one for the fuzzy controller under study.

Table 1. Results of evaluating the fuzzy control rules for all combinations of inputs when e* and r* are within the intervall[-L, L].

Input combination of e* and r*	Membership obtained by evaluating fuzzy control rules			
	R1	R2	R3	R4
$(IC1)_1$	μ_{RP}	μ_{RN}	μ_{EN}	μ_{EN}
$(IC2)_1$	μ_{RP}	μ_{RN}	μ_{EN}	μ_{EN}
$(IC3)_1$	μ_{EP}	μ_{RN}	μ_{EN}	μ_{RN}
$(IC4)_1$	μ_{EP}	μ_{RN}	μ_{EN}	μ_{RN}
$(IC5)_1$	μ_{EP}	μ_{EP}	μ_{RP}	μ_{RN}
$(IC6)_1$	μ_{EP}	μ_{EP}	μ_{RP}	μ_{RN}
$(IC7)_1$	μ_{RP}	μ_{EP}	μ_{RP}	μ_{EN}
$(IC8)_1$	μ_{RP}	μ_{EP}	μ_{RP}	μ_{EN}

In the same manner, Table 2 shows the results of evaluating the fuzzy control rules for all combination of inputs when the scaled ratio r* and acc a* are within the interval[-L, L], for the case of Fig. 6.

Notice that

$$\mu_{RP} = [GR*r(nT) + L]/2L \quad (7)$$
$$\mu_{RN} = [L - GR*r(nT)]/2L \quad (8)$$
$$\mu_{AP} = [GA*a(nT) + L]/2L \quad (9)$$
$$\mu_{AN} = [L - GA*a(nT)]/2L \quad (10)$$
$$\mu_{RP} + \mu_{RN} = 1 \quad (11)$$
$$\mu_{AP} + \mu_{AN} = 1 \quad (12)$$

Table 2. Results evaluating the fuzzy control rules for all combinations of inputs when r* and a* are within the intervall[-L, L].

Input combination of r* and a*	Membership obtained by evaluating fuzzy control rules			
	R1′	R2′	R3′	R4′
$(IC1)_2$	μ_{AP}	μ_{AN}	μ_{RN}	μ_{RN}
$(IC2)_2$	μ_{AP}	μ_{AN}	μ_{RN}	μ_{RN}
$(IC3)_2$	μ_{RP}	μ_{AN}	μ_{RN}	μ_{AN}
$(IC4)_2$	μ_{RP}	μ_{AN}	μ_{RN}	μ_{AN}
$(IC5)_2$	μ_{RP}	μ_{RP}	μ_{AP}	μ_{AN}
$(IC6)_2$	μ_{RP}	μ_{RP}	μ_{AP}	μ_{AN}
$(IC7)_2$	μ_{AP}	μ_{RP}	μ_{AP}	μ_{RN}
$(IC8)_2$	μ_{AP}	μ_{RP}	μ_{AP}	μ_{RN}

2.3 Defuzzification algorithm

In this research, the center of area method is used as the defuzzification algorithm, which amounts to a normalization of the grades of membership of the members of the fuzzy set being defuzzified to a sum of one. Thus the defuzzified output of a fuzzy set is defined as

$$dU = \frac{\sum(membership\ of\ member) * (value\ of\ member)}{\sum(memberships)} \tag{13}$$

The value, used in the defuzzification algorithm, for example the defuzzification algorithm for the control block 1, is the value for the members of the fuzzy set "output1" which are chosen as those values for which the grade of membership in [-L, L] is unity, that is, those values for which the grade of membership is maximum. Therefore, these values are L for the fuzzy member OP, 0 for the fuzzy member OZ and -L for the fuzzy member ON as shown in Fig. 3.

The values used in the defuzzification algorithm for the fuzzy control block 2 are $\frac{L}{2}$ for the fuzzy member OPM and $-\frac{L}{2}$ for the fuzzy member ONM.

When the defuzzification algorithm given as eq. (13) is applied to Table 1, in case the Lukasiewicz OR is used for the membership of the member OZ of the fuzzy set "output1", the incremental output of the fuzzy control block 1 at sampling time nT, $dU_1(nT)$, can be described by the following two equations.

If $GR * |r(nT)| \le GE * |e(nT)| \le L$,

$$dU_1(nT) = \frac{0.5 * L}{2L - GE * |e(nT)|}[GE * e(nT) + GR * r(nT)] \tag{14}$$

If $GE * |e(nT)| \le GR * |r(nT)| \le L$,

$$dU_1(nT) = \frac{0.5 * L}{2L - GR * |r(nT)|}[GE * e(nT) + GR * r(nT)] \tag{15}$$

These results can be observed with careful examination of Fig. 5 and Table 1.

If scaled error and/or scaled rate are not within the interval [-L, L] of the fuzzification algorithm shown in Fig. 2, the incremental output of the fuzzy control block 1 is as listed in Table 3.

Table 3. The incremental output of the fuzzy controller when e* and/or r* are not within the interval [-L, L] of the fuzzification algorithm.

Input combinations as shown in Fig .5	Incremental output of the fuzzy control block 1, $dU_1(nT)$
$(IC9)_1$, $(IC10)_1$	$[GR*r(nT)+L]/2$
$(IC11)_1$, $(IC12)_1$	$[GE*e(nT)+L]/2$
$(IC13)_1$, $(IC14)_1$	$[GR*r(nT)-L]/2$
$(IC15)_1$, $(IC16)_1$	$[GE*e(nT)-L]/2$
$(IC17)_1$	L
$(IC18)_1$, $(IC20)_1$	0
$(IC19)_1$	-L

In a similar fashion, when the defuzzification algorithm is applied to Table 2, the incremental output of the fuzzy control block 2 at sampling time nT, $dU_2(nT)$, can be given by the following two equations.

If $GA * | a(nT) | \le GR * | r(nT) | \le L$,

$$dU_2(nT) = \frac{0.25 * L}{2L - GR * | r(nT) |} [GA * a(nT)] \tag{16}$$

If $GR * | r(nT) | \le GA * | a(nT) | \le L$,

$$dU_2(nT) = \frac{0.25 * L}{2L - GA * | a(nT) |} [GA * a(nT)] \tag{17}$$

If scaled rate and/or scaled acc are not within the interval [-L, L] of the fuzzification algorithm, the incremental output of the fuzzy control block 2 is as listed in Table 4.

Table 4. The incremental output of the fuzzy controller when r* and/or a* are not within the interval [-L, L] of the fuzzification algorithm.

Input combinations as shown in Fig .6	Incremental output of the fuzzy control block 2, $dU_2(nT)$
$(IC9)_2$, $(IC10)_2$, $(IC13)_2$, $(IC14)_2$	0.5*GA*a(nT)
$(IC11)_2$, $(IC12)_2$, $(IC17)_2$, $(IC18)_2$	0.5*L
$(IC15)_2$, $(IC16)_2$, $(IC19)_2$, $(IC20)_2$	-0.5*L

Consequently, the overall incremental output of the FLC, dU(nT), can be obtained by adding incremental output $dU_1(nT)$ from fuzzy control block 1 and incremental output $dU_2(nT)$ out of fuzzy control block 2.

$$dU(nT) = dU_1(nT) + dU_2(nT) \tag{18}$$

Then the crisp value of incremental output, du(nT), can be obtained via multiplying dU(nT) by output scaler GU.

$$du(nT) = GU * dU(nT) \tag{19}$$

Thus far, the process through which the incremental output could be obtained using FLC structure suggested in Fig. 1, was discussed and developed.

Conclusively, the incremental ouput of FLC can be devided into four different forms according to the following conditions:

1) *If* $GR * | r(nT) | \le GE * | e(nT) | \le L$ and $GA * | a(nT) | \le GR * | r(nT) | \le L$,

$$du(nT) = \frac{0.5 * L * GU}{2L - GE * | e(nT) |} [GE * e(nT) + GR * r(nT)] + \frac{0.25 * L * GU}{2L - GR * | r(nT) |} [GA * a(nT)] \tag{20}$$

2) *If* $GR*|r(nT)| \le GE*|e(nT)| \le L$ and
$GR*|r(nT)| \le GA*|a(nT)| \le L$,

$$du(nT) = \frac{0.5*L*GU}{2L - GE*|e(nT)|}[GE*e(nT) + GR*r(nT)] + \frac{0.25*L*GU}{2L - GA*|a(nT)|}[GA*a(nT)] \tag{21}$$

3) *If* $GE*|e(nT)| \le GR*|r(nT)| \le L$ and
$GA*|a(nT)| \le GR*|r(nT)| \le L$,

$$du(nT) = \frac{0.5*L*GU}{2L - GR*|r(nT)|}[GE*e(nT) + GR*r(nT)] + \frac{0.25*L*GU}{2L - GR*|r(nT)|}[GA*a(nT)] \tag{22}$$

4) *If* $GE*|e(nT)| \le GR*|r(nT)| \le L$ and
$GR*|r(nT)| \le GA*|a(nT)| \le L$,

$$du(nT) = \frac{0.5*L*GU}{2L - GR*|r(nT)|}[GE*e(nT) + GR*r(nT)] + \frac{0.25*L*GU}{2L - GA*|a(nT)|}[GA*a(nT)] \tag{23}$$

If scaled error, rate and/or acc are not within the interval [-L, L] the incremental output of the FLC is obtained from the combinations of incremental outputs for the fuzzy control blocks given as Table 3 and Table 4.

Here, if we carefully observe eq. (20), then we can find important fact described as below.

$$du(nT) = \frac{0.5*L*GU*GE}{2L - GE*|e(nT)|} * e(nT) + \frac{0.5*L*GU*GR}{2L - GE*|e(nT)|} * r(nT) + \frac{0.25*L*GU*GA}{2L - GR*|r(nT)|} * a(nT) \tag{24}$$

Let

$$K_i = \frac{0.5*L*GU*GE}{2L - GE*|e(nT)|}$$
$$K_p = \frac{0.5*L*GU*GR}{2L - GE*|e(nT)|}$$
$$K_d = \frac{0.25*L*GU*GA}{2L - GR*|r(nT)|} \tag{25}$$

Then we can obtain the following equation and can find that the fuzzy controller in this research is considered as a nonlinear PID controller with K_p, K_i and K_d changing with error, rate and acc.

$$du(nT) = K_i * e(nT) + K_p * r(nT) + K_d * a(nT) \tag{26}$$

This nonlinear PID controller may be named as nonlinear fuzzy PID controller, where K_p is defined proportional gain, K_i defined integral gain and K_d defined derivative gain.

In a similar fashion, K_p, K_i and K_d can also be obtained for eqs. (21)~(23). We also define the constant proportional gain K_p^*, integral gain K_i^* and derivative gain K_d^* when error, rate and acc are zero. Then they are defined as following from eq. (25) and they are always the same through all conditions.

$$K_p^* = \frac{GU*GR}{4},\ K_i^* = \frac{GU*GE}{4},\ K_d^* = \frac{GU*GA}{8} \tag{27}$$

There are infinitely many combinations of GE, GR, GA and GU so that eq. (27) may hold true. Once GE, GR and GA are selected, GU can be uniquely determined to satisfy eq. (27).

In general, most of model-based conventional control techniques are hard to be applied for controlled processes whose mathematical models cannot be defined or partially defined and for controlled processes whose dynamical characteristics exibit high nonlinearities so that modeling errors resulted from linear approximations affect seriously on control performance. But nonlinear fuzzy PID control method suggested in this paper can be readily applied only if constant proportional gain K_p^* is selected from input/output data so that K_p^* may satisfy rising time requirement in controller design specification, regardless of inperfect model information or nonlinearities.

A design procedure for a suggested nonlinear fuzzy PID controller is as follows.

Step 1 : Input scalers GE, GR and GA for error, rate and acc, respectively, are properly selected from input/output data of controlled process.

Step 2 : Constant proportional gain K_p^* is selected so that it may satisfy rising time requirement in controller design specification.

Step 3 : Then output scaler GU is decided and also constant integral gain K_i^* and constant derivative gain K_d^* are decided from eq. (27).

Step 4 : The linear PID control parameters obtained from step 2 and step 3, should be tuned in order for controlled process to exhibit better transient behavior.

Step 5 : When constant PID gains are tuned prorerly, a nonlinear fuzzy PID control law results from substituting constant PID gains into eqs. (20)-(23).

Ⅲ. Computer simulations

In order to assure the performance and the effectiveness of fuzzy PID controller, computer simulations were executed for the following examples.

(1) Plant transfer function $\frac{10}{s(s+1)}$

This example is an illustration of stable undamped system. It is used to test whether nonlinear fuzzy PID controller improves transient response or not even when model information cannot be used at all.

The results were given in Fig. 7. As was shown, nonlinear fuzzy PID control system exhibits a good unit step response with nearly zero overshoot, faster rising time and more satisfactory settling time than those of nominal plant and nonlinear fuzzy PI control system. In this respect, it is verified that the nonlinear fuzzy PID controller can be designed only using input/output information about controlled plant.

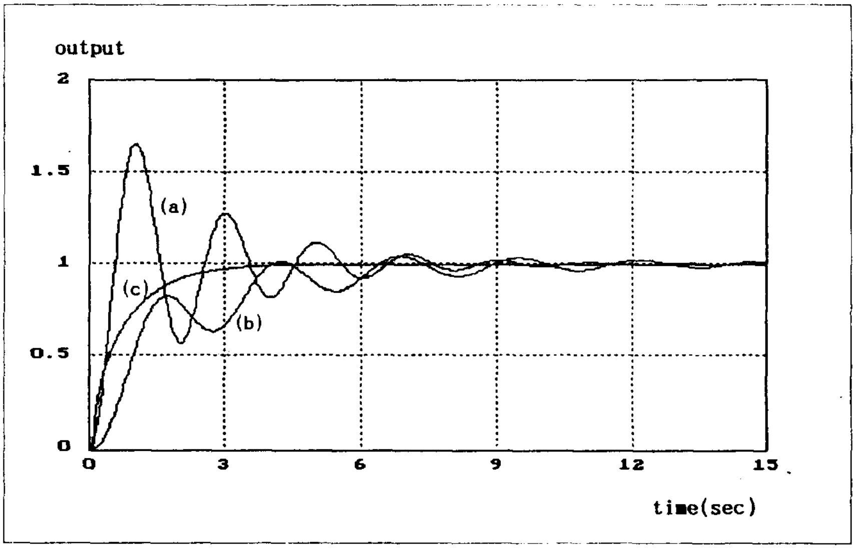

Fig 7. Comparison of unit step responses (a) nominal plant (b) nonlinear fuzzy PI (c) nonlinear fuzzy PID

(2) Plant described by nonliner differential equation $\ddot{y} + \dot{y} = 0.5y^2 + 2u$

This example is an illustration of nonlinear system which is diverged exponentially and slowly. This is used to assure that nonlinear fuzzy PID has a nonlinear characteristics and is stable controller.

The results were shown in Fig. 8. As was shown, nonlinear fuzzy PID exhibits a good transient response and stable control action despite of divergent nominal controlled process. While nonlinear fuzzy

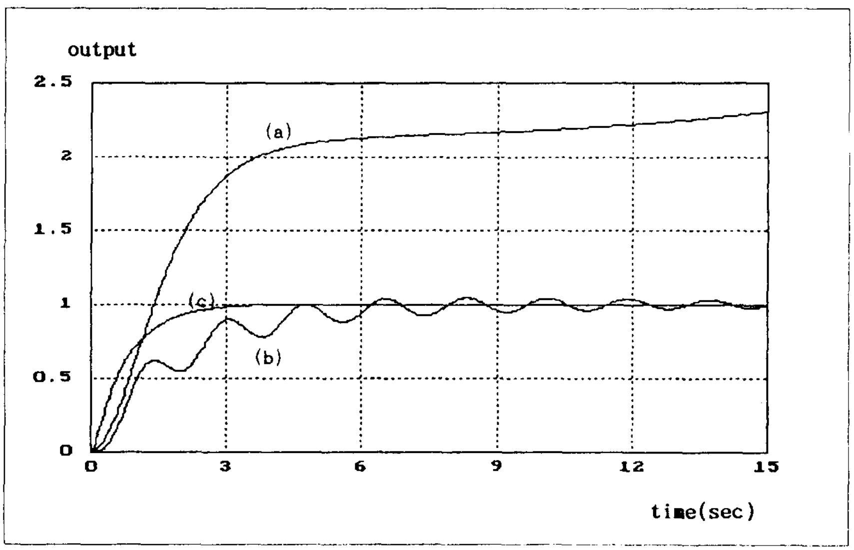

Fig 8. Comparison of unit step responses (a) nominal plant (b) nonlinear fuzzy PI (c) nonlinear fuzzy PID

PI does not diverge but exhibits a poor transient. In this respect, it is noted that the fuzzy PID controller turns out nonlinear controller and exhibits good stable performance without regard for controlled plant to be linear or nonlinear.

(3) Plant transfer function $\frac{e^{-0.2s}}{s(s+1)}$

This example is an illustration of time delay or nonminimum phase system.

The simulation results were given in Fig. 9. As was expected, the nonlinear fuzzy PID exhibits better performance than that of plant and nonlinear fuzzy PI.

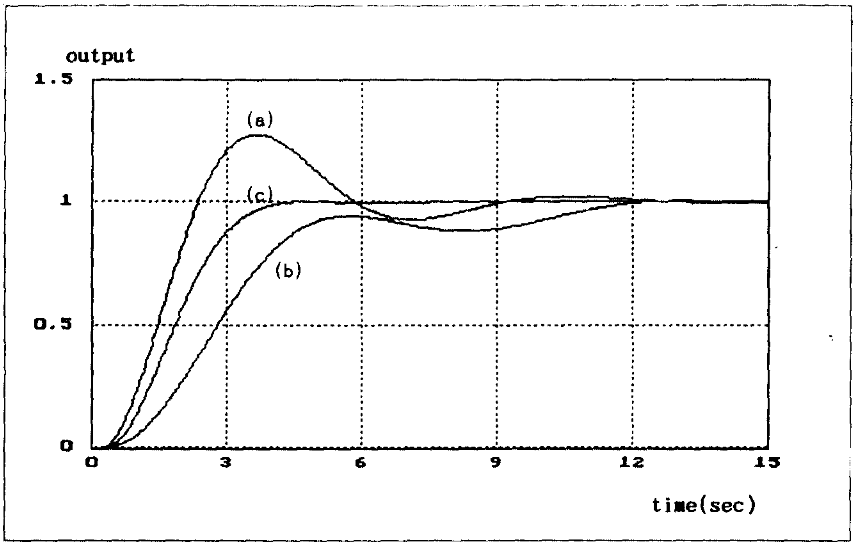

Fig 9. Comparison of unit step responses (a) nominal plant (b) nonlinear fuzzy PI (c) nonlinear fuzzy PID

By the way, in the design of nonlinear fuzzy PID controller suggested in this paper, it also was known that the combination of GE, GR, GA based on nominal plant input/output relation and GU based on proportional gain K_p^* must be selected carefully, especially proportional gain K_p^* used to decide GU, against the possibility of divergence. According to the simulation experience, when controlled process is stable minimum phase system, the selection of K_p^* may be allowed to be the value slightly greater than unity and then the performance may not nearly be different regardless of variant values of K_p^*. But when controlled process is nonlinear and/or nonminimum phase system, K_p^* must be selected carefully as the value smaller than unity, which must not generate exceeded control input as GU is varied and must be tuned step by step with small incremental values to obtain stable desired output.

Ⅳ. Conclusion

In this paper, a nonlinear fuzzy PID control algorithm was derived in order to control nonlinear systems or uncertain systems. The nonlinear fuzzy PID controller derived has the characteristics of nonlinear controller with time varying control parameters and is expecially powerful for the linear and nonlinear time invariant systems, but must be carefully designed for the nonmimum phase system.

The most important advantage of nonlinear fuzzy PID controller is that it is possible to design control system whose plant dynamics, so called mathematical model, is not known, by only using the input/output information. Also, linear PID controller can naturally be derived under the procedure of nonlinear fuzzy PID controller, although plant dynamics is not known.

The usefulness and effectiveness were assured through the computer simulations for several example systems. As the resultant control law has analytical forms and the number of decision making is not much, controller designers can expect effecient design of control system in real time with good transient performance by only employing common-used versatile microprocessors without computational burden.

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