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Dialogical Design of Fuzzy Controller Using Rough Grasp of Process Property

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Abstract: It is the purpose of this paper to present a dialogical designing method for control system using a rough grasp of the unknown process property. We deal with a single-input single-output feedback control system with a fuzzy controller. The process property is roughly estimated by the step response, and the fuzzy controller is interactively modified according to the operator's requests. The modifying rules mainly derived from computer simulation are useful for almost every process, such as an unstable process and a non-minimum phase process.

The fuzzy controller is tuned by taking notice of four characteristics of the step response: (1) rising time, (2) overshoot, (3) amplitude and (4) period of vibration. The tuning position of the controller is fourfold: (1) antecedent gain factor GE or GCE, (2) consequent gain factor GDU, (3) arrangement of the antecedent fuzzy labels and (4) arrangement of the control rules. The rules give an instance to the respective items of the controller in an effective order.

The modified fuzzy PI controller realizes a good response of a stable process. However, because the GDU tuning becomes difficult for the unstable process, it is necessary to evaluate the stability of the process from the initial step response.

The fuzzy PI controller is applied to the process whose initial step response converges with GDU tuning. The fuzzy PI controller with modified sampling time is applied to the process whose step response converges under the repeated application of the GDU tuning. The fuzzy PD controller is applied to the process whose step response never converges by the GDU tuning.

1. INTRODUCTION

As for the unknown process which is stable or unstable, or has an integral element, a dialogical designing method of fuzzy control system based on the knowledge of a fuzzy PI/PD controller is studied. The fuzzy controller in this paper is twofold: One is a fuzzy PI controller, the consequent of which consists of a change of the manipulated variable. Another is a fuzzy PD controller which has the consequent composed of the manipulated variable. The support set of fuzzy variables in antecedent/consequent of the fuzzy controller is normalized over the interval [-1,1], and the corresponding values of the input/output of the controller relate to the set with gain parameters.

The membership function of E. and C.E. in the antecedent has a triangle shape. In the basic formation, seven fuzzy variables are arranged at constant intervals continuously. There are various six formations which have from sparse to dense arrangement in the central area.

The membership function of U. and D.U. is a singleton, and 19 singletons are arranged at constant intervals in the consequent.

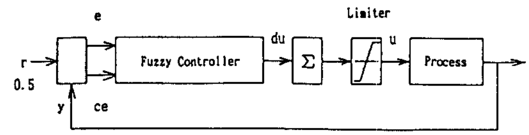

Fig.1 Fuzzy PI Control System

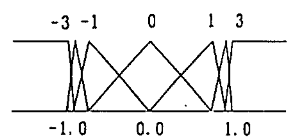

Fig.2(a) Sparse Arrangement in Central Area

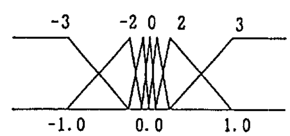

Fig.2(b) Dense Arrangement in Central Area

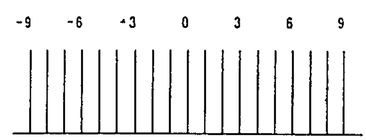

Fig.2(c) Membership Function for Consequent

Table.1 Fundamental Control Rules

ce\e	-3	-2	-1	0	1	2	3
3	0	3	6	9	9	9	9
2	-3	0	3	6	9	9	9
1	-6	-3	0	3	6	9	9
0	-9	-6	-3	0	3	6	9
-1	-9	-9	-6	-3	0	3	6
-2	-9	-9	-9	-6	-3	0	3
-3	-9	-9	-9	-9	-6	-3	0

A fuzzy controller for an unknown process is designed dialogically with a rough grasp of its characteristics using a step response and by tuning the gain parameter of the controller for realizing a good response. The knowledge for modifying is mainly derived from computer simulation. In the concrete, the step response in the initial condition is forced to converge with GDU tuning formula, then the response is modified with the modifying rules according to the requests.

2. GDU TUNING and FUNDAMENTAL MODIFICATION of RULES

The initial gain parameter values of the controller are chosen as follows: (1) GE=1/r, (2) GCE=10·GE, (3) GDU=u_{max}, (4) the formation of the fuzzy variables in the antecedent is basic one, and (5) the control rules are basic ones.

The controller is modified with respect to the following four characteristics of the step response: (1) Rising Time, (2) Overshoot, (3) Amplitude of vibration, and (4) Period of vibration.

The tuning position of the controller is fourfold: (1) antecedent gain factor GE, GCE, (2) consequent gain factor GDU, (3) the arrangement of fuzzy variables in the antecedent, and (4) the arrangement of control rules.

Initial tuning formula with GDU for converging the step response is derived from many computer simulations. As for a stable process, the GDU tuning formula is expressed as follows:

$$GDU=[\text{Set Point}]\times\frac{[\text{Sampling Time}]}{[\text{Time to First Maximum Value}]}\times\frac{[u_{max}]}{[y_{max}]}$$

In this initial tuning formula as to GDU, the first, the second and the third term on the right are concerned with the set point, the time constant/dead-time of the process, and the total gain of the control system respectively.

After applying the above formula, the modifying rules for the individual charavteristics (shown in Table 2-5) will be applied according to a designer's request.

In these tables, the items are shown by order of the improvement effect for the requests. Therefore, the rules may be applied in regular order.

Table. 2 Modifying Rules for Rising Time

No	Items	Modifying Rising Time Making Short
1	GDU	GDU×0.5
2	GCE	GCE×0.6
3	Membership Function of Error	Making arrangment more densely
4	Membership Function of C.E.	Making arrangement more sparsely
5	I Components in Outer Rules	Altering the fixed components into +2
6	P Components in Outer Rules	Altering the fixed components into -2

The items of No.5 and No.6 are concerned with modifying the control rules, and the components of the consequent shown in Table.6 should be altered into those values.

Table. 3 Modifying Rules for Overshoot

No	Items	Modifying Overshoot Making Smaller
1	GDU	GDU×0.6
2	GCE	GCE×1.5
3	Membership Function of Error	Making arrangement more sparsely
4	Membership Function of C.E.	Making arrangement more densely
5	I Components in Outer Rules	Altering the fixed components into -2
6	P Components in Outer Rules	Altering the fixed components into +2
7	P Components in Inner Rules	Altering the fixed components into +2
8	I Components in Inner Rules	Altering the fixed components into -2

Table. 4 Modifying Rules for Amplitude of Vibration

No	Items	Modifying Amplitude of Vibration Making Smaller
1	GDU	GDU×0.85
2	GCE	GCE×1.16
3	Membership Function of Error	Making arrangement more sparsely
4	Membership Function of C.E.	Making arrangement more densely
5	I Components in Inner Rules	Altering the fixed components into -2
6	P Components in Inner Rules	Altering the fixed components into +2

Table. 5 Modifying Rules for Period of Vibration

No	Items	Modifying Period of Vibration Making Longer
1	GDU	GDU×0.85
2	GCE	GCE×0.85
3	Membership Function of Error	Making arrangement more sparsely
4	Membership Function of C.E.	Making arrangement more sparsely
5	I Components in Inner Rules	Altering the fixed components into -2
6	P Components in Inner Rules	Altering the fixed components into -2

* When the step response is a persistent vibration, these rules are applied in the opposite way.

** To modify in the opposite direction, the rules should be applied in the opposite way.

Table. 6 Outer Rules / Inner Rules

C.E. \ Error	-3	-2	-1	0	1	2	3
3	—	Out P	Out P	Out P	—	—	—
2	Out I	—	Out P	Out P	—	—	—
1	Out I	Out I	—	In P	—	—	—
0	Out I	Out I	In I	—	In I	Out I	*Out I
-1	—	—	—	In P	—	Out I	Out I
-2	—	—	—	Out P	Out P	—	Out I
-3	—	—	—	Out P	Out P	Out P	—

The control rules start at the point of (E., C.E.) = (3, 0), and is applied in clockwise. Therefore, the outer rules are concerned in the transient state of the step response, and they are available in improving Rising Time or Overshoot. On the other side, the inner rules are concerned in the steady state of the step response, and they are available in improving Amplitude of Vibration or Period of Vibration. Furthermore, I components are concerned with the integral adjustment (E.), and P components are concerned with the propotional adjustment (C.E.).

The fuzzy PI controller modified by the above knowledge realizes a good step response for a stable process according to the operator's requests.

3. DISCRIMINATING STABILITY/UNSTABILITY OF PROCESS

The GDU tuning is very important and indispensable to designing a fuzzy PI controller. However, because the GDU tuning becomes difficult for an unstable process, it is necessary to discriminate the stability of the process by the step response in the initial condition. The GDU tuning is applied according to the result of discriminating.

The processes whose step responses in the initial condition diverge are outside the range of the present method now. Mostly, these processes are unstable because of including two or more unstable poles, or having a long dead-time.

As for the processes whose step responses in the initial condition do not diverge, we can discriminate their stability by the positive or negative sign of the manipulated variable 'U' in the step response in the initial condition. Concerning the stable process, the manipulated variable in the initial condition occupies mostly the positive values. On the other hand, concerning the unstable process, the manipulated variable in the initial condition occupies mostly the negative values. When the manipulated variable vibrates, the stability of the process is discriminated by the positive or negative sign of the center of vibration. Besides, when the manipulated variable occupies all over the interval [-1.0, 1.0] and the center of vibration is estimated at zero, the stability of the process is discriminated by the positive or negative sign of the average of the manipulated variable in one period.

4. FUZZY PI CONTROLLER FOR STABLE PROCESS

4.1 Applied Range of Modifying Rules for Fuzzy PI Controller

As for the fuzzy PI controller for the stable process, first, the step response in the initial condition is forced to converge with the GDU tuning, and secondly the step response is modified according to the operator's requests by the modifying rules.

As the result of the computer simulation for various processes, the following cases are reached: (1) The GDU tuning cannot be available, (2) the response doesn't converge by using the GDU tuning, (3) the item with GDU in modifying rules does'nt hold good.

Case 1: GDU tuning not available

When the step response in the initial condition becomes a low frequency vibration, the GDU tuning is available, but if the response includes a high frequency vibration, the GDU tuning cannot be available. Where the high frequency vibration is defined as having a short period less than a double sampling period.

In such high frequency vibration, the first maximum value of the response is not definite. Then, because the reaching time to the first maximum value cannot be clear, the GDU tuning which uses this reaching time cannot be available. Under such circumstances, the persistent vibration of the responses are classified in two types, that is, the center of vibration is (a) plus, and (b) minus. According to the classified result, GDU is multiplied by (a) 0.3 or (b) 0.01, and the response is forced to converge with GDU modified recursively.

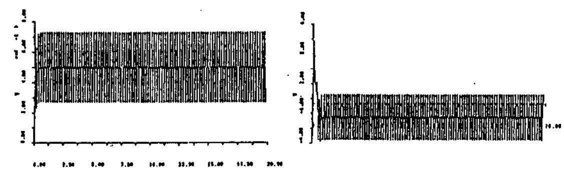

Fig.3 Two Types of High Frequency Vibration

In spite of a low frequency vibration of the step response, when the response overruns the allotted interval and becomes a square wave, the GDU tuning isn't available. Now, we defined the square wave to overrun the allotted interval more than a double sampling period. The reason why the GDU tuning isn't available is that such a square wave doesn't have a unique reaching time to the first maximum value. Therefore, we have to redefine the first maximum value in the square wave vibration to be the end value in the first maximum values. The GDU tuning can be available with the redefined reaching time according to the above first maximum value.

Case 2: Response doesn't converge by using GDU tuning

The GDU tuning formula estimates an approximate value of GDU for converging the response. However, the response occasionally results in a persistent vibration in spite of the GDU tuning. With respect to such responses, it is necessary to apply the GDU tuning recursively.

Finally, the responses are classified in two patterns:

(1) With applying recursively the GDU tuning, the response converges. - According to the computer simulation, though the response converges, the vibration remains a little, when the response speed of the process is very slow or the characteristics of the process is vibrative.

At first, as the dead-time becomes longer, the available range of the GDU tuning becomes narrower. However, when the dead-time exceeds a certain limit, the available range of the GDU tuning becomes wider again. Because the GDU tuning formula includes the term of the reaching time to the first maximum value in the denominator, the GDU tuning value becomes very small for a very large dead-time.

(2) In spite of applying recursively the GDU tuning, the response doesn't converge. - The response doesn't converge but the period of the persistent vibration becomes longer. For such a process, a fuzzy PI controller seems not available. Because the characteristics of the process are chiefly influenced by an integral element, a fuzzy PD controller is more profitable than a fuzzy PI controller. Therefore, after resetting the condition, the fuzzy PD controller should be applied.

Case 3: Item on GDU in modifying rules does'nt hold good.

About the process with a slow response speed, the item on GDU in modifying rules doesn't hold good. As the GDU becomes larger, the overshoot becomes smaller, contrarily thus far.

4.2 Changing Sampling Time

In the above section 4.1, we described the GDU tuning for various processes. However, when the sampling time is fixed as 0.1 [s], there are some processes whose responses don't converge under the GDU tuning. For such processes, the GDU tuning by changing the sampling time is studied. The sampling time influences the characteristics of the process as shown in Fig.4.

Long ←	Sampling Time	→ Short
Long ←	Rising Time	→ Short
Small ←	Overshoot	→ Large
Small ←	Amplitude of Vibration	→ Large
Long ←	Period of Vibration	→ Short

Fig.4 Influence of Sampling Time

4.3 Sampling Time, Dead-time and Time Constant

We studied about the relation between the sampling time and the dead-time in the first order process, and reached the following conclusions:

(1) In spite of applying one time the GDU tuning, the response of some process becomes a persistent vibration.

(2) There is a certain limit of the sampling time where the GDU tuning holds good.

(3) As the dead-time becomes longer, it becomes more difficult to apply the GDU tuning in a short sampling time.

Process without Dead-time: About the process without a dead-time, a short sampling time should suppress the vibration of the response. Usually, a short sampling time doesn't change the overshoot but can make the rising time short.

Process with Dead-time: About the process with a dead-time, as the sampling time becomes shorter, the reaching time becomes shorter, the vibration of the response occurs, and the overshoot becomes larger. When the sampling time exceeds the limit, the vibration of the response becomes persistent. As the dead-time is longer, it is more difficult to apply the GDU tuning in a short sampling time.

Sampling time and Time Constant:

Concerning the process with a dead-time, when a persistent vibration occurs in a certain sampling time after applying the GDU tuning, changing the time constant small makes the GDU tuning suppress the persistent vibration. When the time constant is small, the GDU tuning becomes easy in a short sampling time.

Regarding a second order process, like a first order process, as the sampling time becomes shorter, the rising time becomes shorter and the vibration gradually occurs. However, as the dead-time becomes longer, the GDU tuning becomes easier in a short sampling time contrary to a first order process.

The above discussion leads to the following conclusions: The process to which the GDU tuning doesn't hold good is in the area of a persistent vibration. For such process, the GDU tuning will be available in a longer sampling time. However, because too long sampling time makes the rising time be too long, it becomes difficult to modify the rising time after GDU tuning. On account of this, the optimum sampling time depends on what the operator regards as most important among the characteristics of the response.

For example, if the rising time is regarded as most important, the sampling time should be shortest where the GDU tuning is available, and the GDU tuning is applied many times. On the other hand, if the small overshoot is regarded as most important, though the rising time becomes long, the sampling time shold be long. Moreover, when the vibration remains a little in the converged response with applying the GDU tuning repeatedly, the vibration may be suppressed with changing the sampling time.

Changing the sampling time works well not only for the GDU tuning but also for the requests which are out of the range of the modifying rules.

How changing the sampling time is shown in Fig.5.

Requests	Sampling Time
Making Rising Time short	Making long
Making Overshoot small	Making short
Making Amp. of Vib. small	Making short
Making Per. of Vib. long	Making short

Fig.5 Change of Sampling Time for Requests

Concerning the influences of changing the sampling time, the original modifying rules still work well according to the requests without changing the order of modifying the items. However, for making the rising time short, it becomes necessary to apply the rules many times because of the slow response. So, the modifying value should be improved to realize a fast response.

5. FUZZY PI CONTROLLER FOR UNSTABLE PROCESS

5.1 GDU TUNING

The GDU tuning for an unstable process should be applied according to the step response in the initial condition. When the response is a high frequency vibration, there are following four patterns: (1) A cyclic and persistent vibration whose average doesn't exceed the set point, (2) a cyclic and persistent vibration whose average exceeds the set point, (3) a cyclic and persistent vibration superposed by a low frequency vibration, and (4) a non-cyclic and persistent vibration.

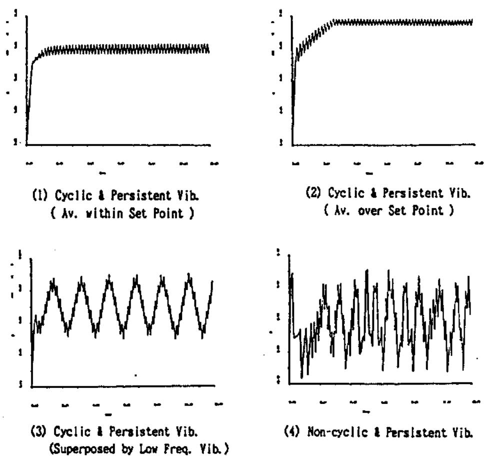

Fig.6 Unstable/High Freq. Responses

The modifying value shown in Fig.7 is approximate and derived by the computer simulation. From the item (1) to (4), the modifying width gradually becomes large, because of the unstability with the large GDU gain.

If the vibration doesn't converge by modifying only one time, the modifying rule should be applied repeatedly. When the response becomes diverging, it can be suppressed by changing GCE larger.

Pattern of Response	Modifying
Cyclic & Persistent Vibration	
(1) whose av. doesn't exceed the S.P.	GDU×0.9
(2) whose av. exceeds the S.P.	GDU×0.4
(3) superposed by a low freq. vibration	GDU×0.4
Non-cyclic & Persistent Vibration	GDU×0.1

Fig.7 GDU Tuning for Unstable Process

If the vibration is not a high frequency, the GDU tuning and the rearranging of the membership function of the error are effective for suppressing the persistent vibration. If the response becomes diverging under modifying, changing the membership function of the error or changing the outer component in the control rules are available.

The GDU tuning for the unstable process is applied in two ways according to the step response in the initial condition. A high frequency vibration occurs almost for the first order process, and other persistent vibration occurs for the second order process. The GDU tuning is available for unknown process with keeping the prescribed procedure.

5.2 DESIGNING FUZZY PI CONTROLLER FOR UNSTABLE PROCESS

A fuzzy PI controller also designed for the unstable process whose step response in the initial condition diverges.

The step responses may be classified into (a) a high frequency and persistent vibration, (b) a low frequency and persistent vibration and (c) a deciduous vibration. Concerning the pattern (a) and (b), after applying GDU tuning described in section 5.1, modifying rules are applied for realizing the response matched with the operator's requests. The pattern (b) is under some restrictions for preventing a persistent vibration once suppressed with the GDU tuning. However, either pattern of (a), (b) and (c) is inclined to recur a vibration or not to suppress the vibration on account of unstability of the process.

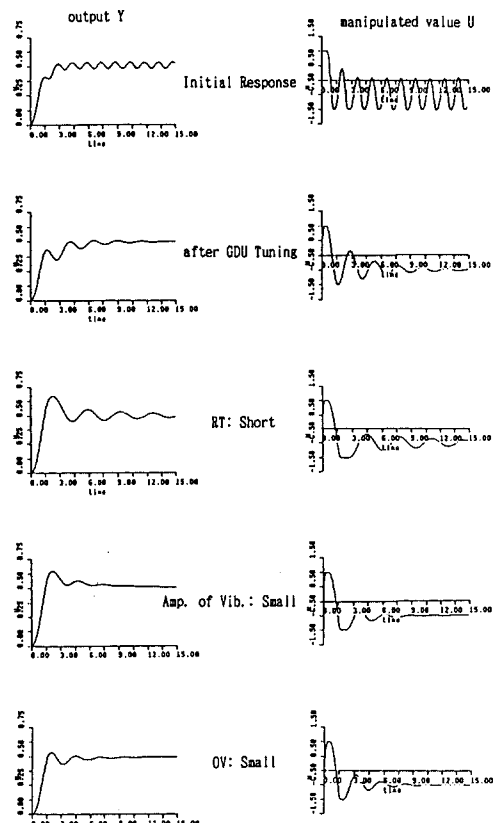

Fig.8 Modifying Path for Step Response of Unstable Process

6. DESIGNING FUZZY PD CONTROLLER

Generally, it is well known that a PD controller is more effective than a PI controller for the process with an integral element. Consequently, a fuzzy PD controller is more available for the process with an integral element.

However, if a fuzzy PD controller is applied to the process without an integral element, the offset occurs and the output of the process never agrees with the reference input.

When the process with an integral element is controlled with a fuzzy PI controller, a vibration of the step response easily occurs and never converges with applying the GDU tuning repeatedly. A fuzzy PD controller may suppress such vibration with ease, but the knowledge for designing the fuzzy PD controller is not sufficient. Therefore, we studied on a stable process with an integral element for getting the knowledge of designing a fuzzy PD controller.

6.1 Fuzzy PD Controller

A fuzzy PD controller inferences the manipulated value 'U' using the error and the change of error. The fuzzy PD controller is modified with respect to the following items:

(1) The range of the control rules - GE, GCE
(2) The control rules
(3) GCE multiplied by C.E. in the antecedent
(4) The membership function of E. and C.E. in the antecedent

The influence of the control rules was small in a fuzzy PI controller, but it becomes large in a fuzzy PD controller. So, the control rules should be modified at first.

The modifying items in a fuzzy PD controller are as follows: (1) Rising Time, (2) Overshoot, (3) Amplitude of Vibration and (4) Period of Vibration.

Concerned with the above four items, the knowledge derived by the computer simulation is shown from Table.7 to Table.10.

For modifying the step response in the initial condition according to the operator's requests, the following procedures from (1) to (5) are performed. If the response matches the requests, modifying will be over.

(1) Changing Range of Control Rules

When the response is a persistent vibration, the modifying rules doesn't hold good. Keeping the ratio of GE and GCE constant, they are multiplied by 0.6 repeatedly, until the response converges or becomes a damped vibration.

If the response converges or becomes a damped vibration, GE and GCE are modified according to the modifying rules under keeping constant the ratio of GE and GCE.

(2) Modifying Control Rules

All labels in the original control rules should be multiplied by a real number. Practically, the adequate one is selected from the prepared five patterns of control rules.

(3) Modifying GCE

The value of GCE is modified according to the modifying rules.

(4) Modifying Membership Function of Error

Making the center area of the membership function more dense or more sparse according to the modifying rules. The membership function is represented by the same way in a fuzzy PI controller.

(5) Modifying Membership Function of C.E.

It should be modified in like manner (4).

Table.7 Modifying Rules for Rising Time

No	Items	Modifying Rising Time
		Making Short
1	GE & GCE	Multiplied by 1.5
2	Control Rule	Making arrangment more densely
3	GCE	GCE×0.6
4	Membership Function of Error	Making arrangement more densely
5	Membership Function of C.E.	Making arrangement more sparsely

Table.8 Modifying Rules for Overshoot

No	Items	Modifying Overshoot
		Making Small
1	GE & GCE	Multiplied by 1.5
2	Control Rule	Making arrangment more densely
3	GCE	GCE×1.5
4	Membership Function of Error	Making arrangement more sparsely
5	Membership Function of C.E.	Making arrangement more densely

Table.9 Modifying Rules for Amplitude of Vibration

No	Items	Modifying Amplitude of Vibration
		Making Smaller
1	GE & GCE	Multiplied by 0.6
2	Control Rule	Making arrangment more sparsely
3	GCE	GCE×1.5
4	Membership Function of Error	Making arrangement more sparsely
5	Membership Function of C.E.	Making arrangement more densely

Table.10 Modifying Rules for Period of Vibration

No	Items	Modifying Period of Vibration
		Making Longer
1	GE & GCE	Multiplied by 0.6
2	Control Rule	Making arrangment more sparsely
3	GCE	GCE×0.6
4	Membership Function of Error	Making arrangement more sparsely
5	Membership Function of C.E.	Making arrangement more densely

7. CONCLUSION

We propose a dialogical modifying method for a fuzzy controller for an unknown process in this paper.

There may be following four steps:

(1) Supplementing the knowledge for designing a fuzzy PI controller for a satable process
(2) Getting the knowledge of a fuzzy PI controller for an unstable process and making some rules
(3) Getting the knowledge of a fuzzy PD controller for a stable process and making some rules
(4) Integrating above three steps and making a fuzzy control system

In step 1, as shown in section 4, we studied the effective range of a conventional modifying rules for a stable process, and worked out a measure for out of the range. Moreover, we investigated the influence of changing the sampling time and made out its effectiveness for the control system.

In step 2 and step 3, as shown in section 5 and section 6, we completed getting the knowledge and making rules.

Regarding step 4, we had to develop a method for discriminating the stability/unstability of the process and a method for discriminating the process with an integral element from another. We could discriminate the process stability by the positive or negative sign of the manipulated variable U in the step response in the initial condition of the fuzzy PI controller. We could also discriminate the process with an integral element by the response in the GDU tuning after the initial step response. If the response becomes better by the GDU tuning, a fuzzy PI controller may be profitable. When the response isn't improved by the GDU tuning, a fuzzy PD controller may be profitable for the process which is considered including an integral element.

After all, we can realize one integrated fuzzy control system with these results. We will carry out further studies in the future to put the present method to practical use.

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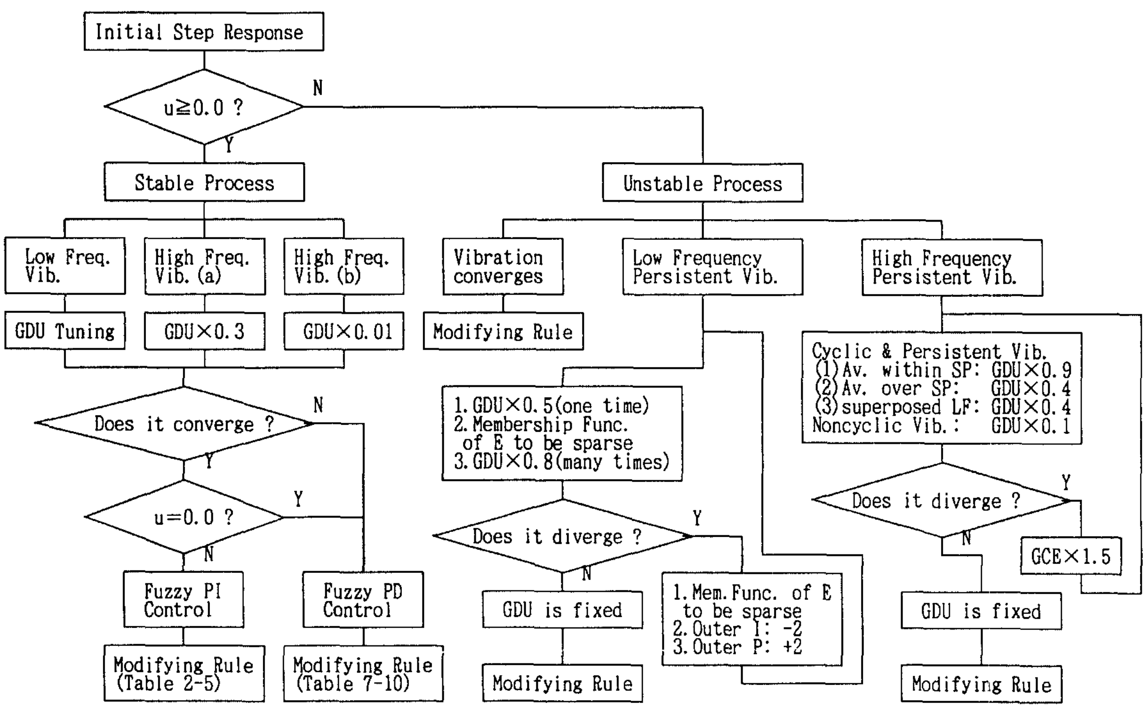

Fig.9 Dialogical Designing Method for Fuzzy Control System