3.SOME ADVANCED PROBLEMS

3.1 Self-regulating of scaling factors on-line

If we always change the FPID parameters on-line,it is meaningless to compute the look-up-table off-line.We meet the problem of large computations that must be solved for the reason of applications.

Procyk and Mamdani ([16]) have analysed the effect of the scaling factors.We summerise some points here: Decreasing GE and GD makes the performance measure more sensitive around the set-point and less sensitive during rise-time.Increasing the two parameters has the opposite effect.A low value of GC results in slow rise-time,a larger integral square error and so extends the area of poorest response but increase the region of fastest convergence.A high value of GC decreases the region of fastest convergence.

It is possible to get a good response by regulating the scaling factors on-line. Using the analysis of [16] and the idea of [21] we may regulate the scaling factors as follows:

$$GD = f_1(E,\frac{dE}{dt})$$

$$GE = f_2(E,\frac{dE}{dt})$$

$$GC = f_3(E,\frac{dE}{dt}).$$

Functions f_1,f_2 and f_3 may be very complex. In this primary study we take f_1 = constant, f_2 = constant and

$$f_3(E,\frac{dE}{dt}) = k_0|E| + k_1$$

where k_0 and k_1 are constants.Digital simulations prove this method is very effective.

For the process $\frac{e^{-0.4S}}{(0.3S+1)^2}$,we use fuzzy PI controller with all the same parameters as in Fig.4 but $GC = 0.15|E| + 0.2$. The response (showed in Fig.5) is better than that when GC fixed. In Fig.5 $y \in [9.93, 9.94]$ after $t > 18$ and $\Delta^2 E = 127.1$ and ITAE = 76.4 whereas $\Delta^2 E = 184.2$, ITAE = 131.7 and $y \in [9.6, 10.4]$ after $t > 18$ in Fig.4 when GC = 0.8 .

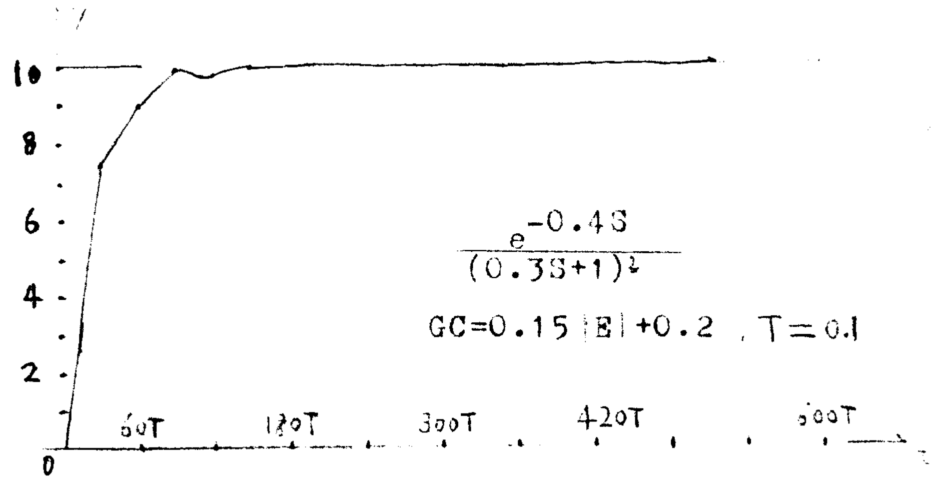

Fig.5 The response under FPI controlling

We have seen in Fig.2 ② that the rise-time is very long for the process $\frac{e^{-0.8S}}{(S+1)(S+2)}$ when GC = 0.8 fixed. If we let $GC = 0.3|E| + 0.15$, then the rise-time is shortened as shown in Fig.6, where $y \in [9.95, 9.97]$ after $t > 15$.

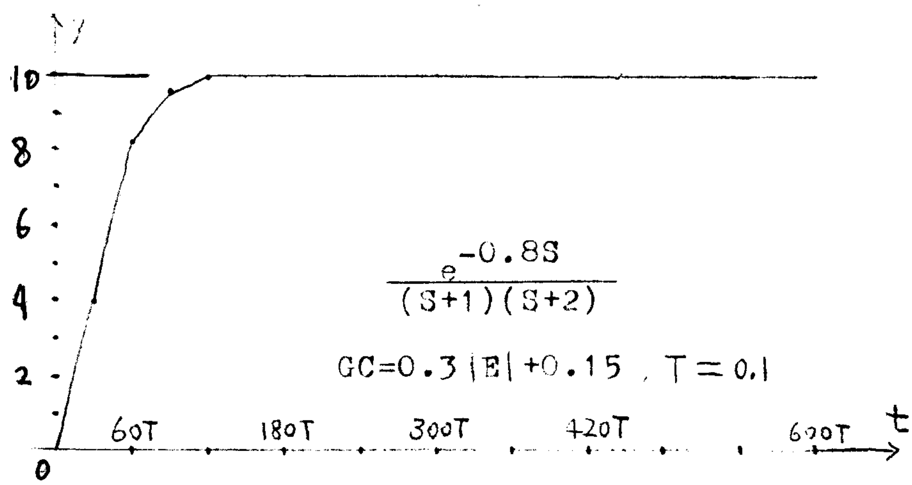

Fig.6 The response under FPID controlling

If a small over-shoot permitted, we can increase k_0 in $GC = k_0|E| + k_1$ to shorten the rise-time and decrease $\Delta^2 E$ and ITAE. For the process $\frac{e^{-0.8S}}{(S+1)(S+2)}$, if all parameters are the same with that in Fig.6 but $GC = 0.6|E| + 0.1$, then the over-shoot is 1 but $\Delta^2 E = 180.6$ and ITAE= 52.4 .The response is shown in Fig.7 .

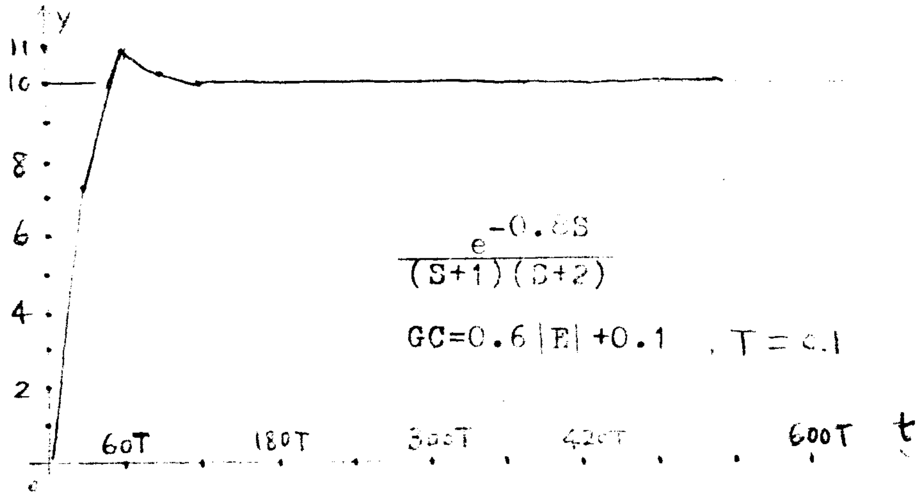

Fig.7 The response under FPID controlling

3.2 Automatically generating linguistic control rules

For a particular process, using optimization techniques we can get the optimal FPID parameters of the FPID controller. Then the linguistic control rules are generated by machine. In fact, in all the former digital simulations the FPID parameters and then the linguistic control rules are generated by machine not by human-brain as in all published literature

After obtaining the control rules the operators' experiences may be used on adjusting scaling factors and analysing those rules with techniques as proposed in [3].

4. ACCURACY OF IMPLICATION OPERATORS

Generally, the linguistic control rules that defined a fuzzy controller may describe the relations between input $x = (x^1, x^2, \ldots, x^n)$ and output (process-input-change) $y = (y^1, y^2, \ldots, y^m)$ as follows.

$$\text{IF } x \text{ is } \alpha_i \text{ THEN } y \text{ is } \beta_i \quad , \ 1 \leq i \leq N .$$

where $\alpha_i = (\alpha_i^1, \alpha_i^2, \ldots, \alpha_i^n)$, $\beta_i = (\beta_i^1, \beta_i^2, \ldots, \beta_i^m)$, α_i^k and β_i^l are linguistic values, $1 \leq i \leq N$, $1 \leq k \leq n$, $1 \leq l \leq m$.

From the N individual rules one can synthesis the fuzzy controller represented by a fuzzy relation:

$$R = R_1 \overset{*}{\vee} R_2 \overset{*}{\vee} \cdots \overset{*}{\vee} R_N$$

where $\overset{*}{\vee}$ is an operator and R_i is obtained from the ith rule:

$$R_i = \alpha_i^1 \overset{\cdot}{*} \alpha_i^2 \overset{\cdot}{*} \cdots \overset{\cdot}{*} \alpha_i^n \overset{*}{\wedge} \beta_i^1 \overset{+}{*} \beta_i^2 \overset{+}{*} \cdots \overset{+}{*} \beta_i^m$$

where $\overset{\cdot}{*}$, $\overset{+}{*}$ and $\overset{*}{\wedge}$ are fuzzy operators.

For any input $x = (x^1, x^2, \ldots, x^n)$ the output fuzzy set is

$$C = x \circledast R$$

where $\circledast$ is a composition operator. The accuracy output y is obtained by a non-fuzzifying operator D:

$$y = D(C).$$

Kiszka, J.B. et al [9] studied 72 definitions of R when n=m=1 for a fuzzy model and obtained the best fuzzy relations R_{2*} and R_{27*} defined as follows:

$$R_{2*}(x,y) = \bigwedge_s \begin{cases} 1 & \text{If } A_s(x) \leq B_s(y) \\ 0 & \text{otherwise.} \end{cases}$$

$$R_{27*}(x,y) = \bigwedge_s \begin{cases} 1 & \text{If } A_s(x) \leq B_s(y) \\ B_s(y) & \text{otherwise.} \end{cases}$$

where the linguistic rules are IF x is A_s THEN y is B_s , $1 \leq s \leq N$.

In the former sections our problem is one when n = 2 or 3, m = 1 and N = 49 or 343. The operators used are $\vee$ (max) and $\wedge$ (min):

$$R = \bigvee_{i,j,k} (L_i \wedge L_j \wedge L_k \wedge L_{f(i,j,k)})$$

We denote this relation by ($\vee$, $\wedge$) and define relations (Σ ,$\cdot$) and ($\vee$,$\cdot$) in the following way:

$$(\Sigma,\cdot):\ R = \sum_{i,j,k} (L_i \cdot L_j \cdot L_k \cdot L_{f(i,j,k)}) \ / \ N$$

$$(\vee,\cdot):\ R = \bigvee_{i,j,k} (L_i \cdot L_j \cdot L_k \cdot L_{f(i,j,k)})$$

where N = 343.

We define R_{2*} , R_{27*} and Lukasiewicz-like ([11]) operator R_{5*}[9] for n=3 as follows:

$$R^1_{2*}(x,y,z,u) = \bigwedge_{i,j,k} \begin{cases} 1 & \text{If } L_i(x) \wedge L_j(y) \wedge L_k(z) \leq L_{f(i,j,k)}(u) \\ 0 & \text{otherwise.} \end{cases}$$

$$R^2_{2*}(x,y,z,u) = \bigwedge_{i,j,k} \begin{cases} 1 & \text{If } L_i(x) \cdot L_j(y) \cdot L_k(z) \leq L_{f(i,j,k)}(u) \\ 0 & \text{otherwise.} \end{cases}$$

$$R^1_{27*}(x,y,z,u) = \bigwedge_{i,j,k} \begin{cases} 1 & \text{If } L_i(x) \wedge L_j(y) \wedge L_k(z) \leq L_{f(i,j,k)}(u) \\ L_{f(i,j,k)}(u) & \text{otherwise.} \end{cases}$$

$$R^2_{27*}(x,y,z,u) = \bigwedge_{i,j,k} \begin{cases} 1 & \text{If } L_i(x) \cdot L_j(y) \cdot L_k(z) \leq L_{f(i,j,k)}(u) \\ L_{f(i,j,k)}(u) & \text{otherwise.} \end{cases}$$

$$R^1_{5*}(x,y,z,u) = \bigwedge_{i,j,k} (1 \wedge (1 - L_i(x) \wedge L_j(y) \wedge L_k(z) + L_{f(i,j,k)}(u)))$$

and

$$R^2_{5*}(x,y,z,u) = \bigwedge_{i,j,k} (1 \wedge (1 - L_i(x) \cdot L_j(y) \cdot L_k(z) + L_{f(i,j,k)}(u)))$$

In order to compare the accuracy of those implication operators, we apply them to the controlling of a process with the same scaling factors and same FPID parameters(i.e.,the same linguistic control rules).

For process $\frac{e^{-0.4S}}{(0.3S+1)^2}$ we select FPID parameters F_p=0.3, F_i=0.45, and F_d=0.15 and scaling factors GD=1,GE=1.667,GH=1 and GC=0.8 . The computation results are listed in Table 1 where $\Delta^2 E = \int_0^{250T} |E(t)|^2 dt$ and $ITAE = \int_0^{250T} t \cdot |E(t)| dt$.

Table 1

Operator	$\Delta^2 E$	ITAE
$(\vee, \wedge)$	199.0	68.8
$(\Sigma, \cdot)$	182.9	69.5
$(\vee, \cdot)$	181.1	68.6
R^1_{2*}	394.0	349.9
R^2_{2*}	394.5	346.9
R^1_{27*}	418.1	351.6
R^2_{27*}	413.5	334.8
R^1_{5*}	207.6	138.9
R^2_{5*}	204.9	113.5

From Table 1 we can classify those operators to three groups:

I : $(\vee, \wedge), (\Sigma, \cdot), (\vee, \cdot)$

II: R^1_{5*} , R^2_{5*}

III: R^1_{2*} , R^2_{2*} , R^1_{27*} , R^2_{27*}

We may conclude that the implication operators must be chosen with respect to various problems but Zadeh's operrator $\vee-\wedge$ is effective always.

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APPENDIX

A1 Linguistic control rules of FPID when $F_p=0.3, F_i=0.45$ and $F_d=0.15$, i.e., the rules for Fig.2, Fig.6 and Fig.7 .

$\ddot{e}$: NB

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NM	NS
NM	NB	NM	NM	NM	NM	NS	NS
NS	NM	NM	NM	NS	NS	NS	ZE
ZE	NM	NM	NS	NS	NS	PS	PS
PS	NS	NS	NS	ZE	PS	PS	PS
PM	NS	NS	PS	PS	PS	PM	PM
PB	ZE	PS	PS	PS	PM	PM	PM

$\ddot{e}$: NM

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	NS
NS	NM	NM	NM	NS	NS	NS	PS
ZE	NM	NS	NS	NS	ZE	PS	PS
PS	NS	NS	NS	PS	PS	PS	PM
PM	NS	ZE	PS	PS	PS	PM	PM
PB	PS	PS	PS	PM	PM	PM	PM

$\ddot{e}$: NS

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NM	NS	NS
NM	NM	NM	NM	NM	NS	NS	NS
NS	NM	NM	NS	NS	NS	ZE	PS
ZE	NM	NS	NS	NS	PS	PS	PS
PS	NS	NS	ZE	PS	PS	PS	PM
PM	NS	PS	PS	PS	PM	PM	PM
PB	PS	PS	PS	PM	PM	PM	PB

$\ddot{e}$: ZE

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NM	NM	NM	NM	NS	NS
NM	NM	NM	NM	NS	NS	NS	ZE
NS	NM	NM	NS	NS	NS	PS	PS
ZE	NS	NS	NS	ZE	PS	PS	PS
PS	NS	NS	PS	PS	PS	PM	PM
PM	ZE	PS	PS	PS	PM	PM	PM
PB	PS	PS	PM	PM	PM	PM	PB

$\ddot{e}$: PM

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NM	NM	NM	NM	NS	NS	NS
NM	NM	NM	NS	NS	NS	ZE	PS
NS	NM	NS	NS	NS	PS	PS	PS
ZE	NS	NS	ZE	PS	PS	PS	PM
PS	NS	PS	PS	PS	PM	PM	PM
PM	PS	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PM	PM	PB	PB

$\ddot{e}$: PB

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NM	NM	NM	NS	NS	NS	ZE
NM	NM	NM	NS	NS	NS	PS	PS
NS	NS	NS	NS	ZE	PS	PS	PS
ZE	NS	NS	PS	PS	PS	PM	PM
PS	ZE	PS	PS	PS	PM	PM	PM
PM	PS	PS	PM	PM	PM	PM	PB
PB	PS	PM	PM	PM	PB	PB	PB

$\ddot{e}$: PS

e \ $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NM	NM	NM	NS	NS	NS
NM	NM	NM	NM	NS	NS	NS	PS
NS	NM	NS	NS	NS	ZE	PS	PS
ZE	NS	NS	NS	PS	PS	PS	PM
PS	NS	ZE	PS	PS	PS	PM	PM
PM	PS	PS	PS	PM	PM	PM	PM
PB	PS	PS	PM	PM	PM	PB	PB

A2 Linguistic control rules of FPI when $F_p=0.3$ and $F_i=0.45$, i.e., rules for Fig.4 and Fig.5 .

ė \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NM	NM	NS	NS	ZE	PS
NM	NM	NM	NM	NS	NS	PS	PS
NS	NM	NM	NS	NS	PS	PS	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	NS	PS	PS	PM	PM
PM	NS	NS	PS	PS	PM	PM	PM
PB	NS	ZE	PS	PS	PM	PM	PB