A Novel Design and Tuning Procedure for PID Type Fuzzy Logic Controllers

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***Abstract*—In this work a new methodology for designing and tuning PID type fuzzy logic controllers (PID-FLC) is presented. The employed PID-FLC is a modified version of a hybrid structure constructed by integrating a PI type FLC and a PD type FLC. First, a direct relationship between the scaling factors of the modified hybrid PID-FLC (MHPID-FLC) and the proportional, integral and derivative actions of its traditional counterpart are established. Thus, based on this relationship, well-known methods used for tuning traditional PID controllers, i.e. the Ziegler-Nichols method, can be used to find the scaling factors of their fuzzy counterparts. A fine tuning procedure, if necessary, can be followed to further improve the MHPID-FLC performance. This fine-tuning can be developed in two ways: 1) modifying the scaling factors, 2) modifying the control surface of the fuzzy control system inside the MHPID-FLC structure; general guidelines for these procedures are given. The effectiveness of this approach is shown in benchmark processes taken from the literature.**

***Index Terms*—PID fuzzy logic controllers, tuning procedure, scaling factors, PID control, two-term fuzzy logic controllers.**

I. Introduction

In traditional control the PI, PD and PID control algorithms are expressed as (to avoid confusion, in this work the symbol * means multiplication):

$$u_{PI}(t) = K_P * e(t) + K_I * \int e(t) * dt = K_P * \left(e(t) + \frac{1}{T_i} * \int e(t) * dt \right) \quad (1),$$

$$u_{PD}(t) = K_P * e(t) + K_D * \frac{de(t)}{dt} = K_P * \left(e(t) + T_d * \frac{de(t)}{dt} \right) \quad (2),$$

$$u_{PID}(t) = K_P * e(t) + K_I * \int e(t) * dt + K_D * \frac{de(t)}{dt} = K_P * \left(e(t) + \frac{1}{T_i} * \int e(t) * dt + T_d * \frac{de(t)}{dt} \right) \quad (3),$$

$$e(t) = y_r(t) - y(t) \quad (4),$$

where e is the error signal, y_r is the set point, y is the process output, $T_i = K_P/K_I$, and $T_d = K_D/K_P$. The terms K_P, K_I and K_D are referred to as the proportional, integral and derivative gains. The parameters T_i and T_d are known as the integral time and the derivative time respectively.

In fuzzy control there are the analogous structures of PI type fuzzy logic controller (PI-FLC), PD type fuzzy logic controller (PD-FLC) and PID type fuzzy logic controller (PID-FLC) [1]-[2]. Their basic structures are shown in Fig. 1; inside these structures a fuzzy control system (FCS) develops the three well-known processes of fuzzification, rule evaluation and defuzzification [1], [3]. The PI-FLC and PD-FLC have been extensively studied [3]-[6]. These two-term FLCs have achieved wide acceptance in both academic research and industrial applications. However, the PID-FLC is considered to be still at its early stage of development as is shown by numerous recent research papers reporting the exploration of different PID-FLC structures [2], [7]-[11].

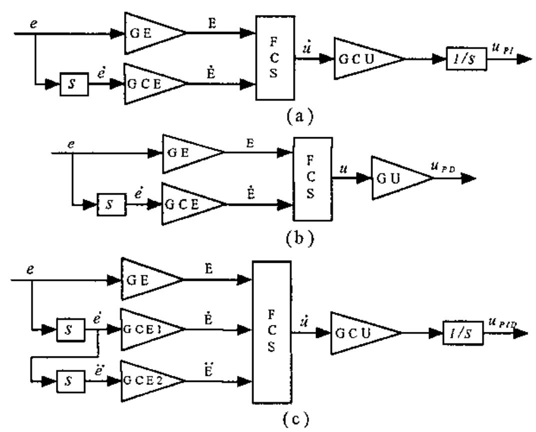

Fig. 1. Structures for (a) PI-FLC, (b) PD-FLC, and (c) PID-FLC.

In the FLC literature several PID-FLC structures have been proposed. Initially, these structures were designed considering three terms as inputs (see Fig. 1) [1], [12]. Obviously, the rule base of these fuzzy controllers is three-dimensional (3-D), which makes it difficult to obtain since 3-D information is usually beyond the sensing capability of a human expert. To overcome this problem, a variety of approaches have been proposed [7], [13]-[14]. A typical method for rule reduction is to divide the three-term PID-FLC into two separate PI and PD parts [2]. Thus two rule bases are used; one for a PI-FLC and

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0-7803-7134-8/02/$10.00 © 2002 IEEE

one for a PD-FLC, the output is obtained by adding the respective crisp control outputs, as shown in Fig. 2(a). This structure has the advantage that both rule bases are two-dimensional avoiding the difficulty of designing a three-dimensional rule base. Consequently the design of a PID rule base becomes the design of both a PI and a PD rule base. These two rule bases share the same inputs, which reduces the tuning complexity.

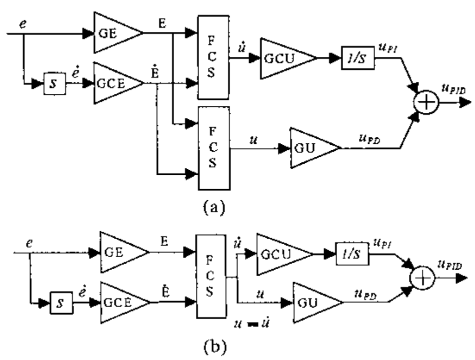

Fig. 2. (a) PI + PD-FLC structure for a PID-FLC, (b) HPID-FLC structure.

Li [15] further develops the above idea. This author proposes the use of a common two-dimensional rule base on a hybrid PID-FLC structure. This rule base is shared for both the PI-FLC and the PD-FLC parts. It means that a hybrid PI and PD control strategy is implemented by simply using a two-term fuzzy control rule base without any increase in the number of rules. This simplifies the PID-FLC structure as it is simpler, easier to implement, and faster in computation. The structure of the hybrid PID-FLC (HPID-FLC) is shown in Fig. 2(b). In this structure, GE and GCE are the input scaling factors, while GU and GCU are the output scaling factors.

This approach does have a disadvantage in that the controller parameters are coupled with each other and have to be regulated in combination. In his work Li [15] gives some general guidelines to find and tune the gains of the HPID-FLC based on those gains obtained for its traditional counterpart. However, this relationship is not direct and results in a quite complicated methodology.

Based on the investigation of the relationship between the three actions of traditional PID control and the scaling factors (from here referred to as SF) of a modified HPID-FLC, in this paper a new methodology for designing and tuning PID-FLC is presented. First, in section II a direct relationship between the proportional, integral and derivative gains of traditional PID control and the SF of the modified HPID-FLC is derived through mathematical analysis and comparison. Then, in section III, a methodology to find the SF of the modified HPID-FLC is given. Next, it is shown how fine-tuning of the SF and further improving the performance of the modified HPID-FLC can be developed. In section IV the viability of the proposed approach is demonstrated by simulating benchmark processes taken from the literature. Finally, conclusions and perspectives are given in section V.

II. Analysis Of The Relationship Between Traditional PID Control And The MHPID-FLC

First, in order to avoid derivative kick in the implementation of (3) a modified derivative term is used. Additionally, when the Ziegler-Nichols tuning formula is applied a set point weighting factor is employed to reduce overshoot [16], thus (3) is transformed as follows,

$$U_{PID}(t) = K_P * \left(\beta * (y_r(t) - y(t)) + \frac{1}{T_i} * \int e(t) * dt - T_d * \frac{dy(t)}{dt} \right)$$
$$= K_P * \beta * y_r(t) - K_P * y(t) + K_I * \int e(t) * dt - K_D * \frac{dy(t)}{dt} \quad (5)$$

Observe in (5) that the derivative term $de(t)/dt$ in (3) has been replaced by $-dy(t)/dt$. The incorporation of the above modification in the HPID-FLC structure modifies it as shown in Fig. 3. This modified HPID-FLC (MHPID-FLC) structure is the one used in this approach.

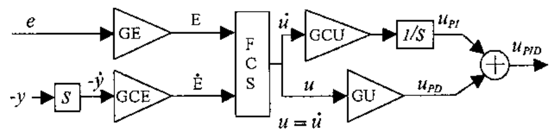

Fig. 3. Modified HPID-FLC (MHPID-FLC) structure.

Next, if the following assumptions are made:

1. The FCS inside the MHPID-FLC structure is a first-order Takagi-Sugeno fuzzy model [17], [18], with fuzzy rules of the form:
   If E is A and $\dot{E}$ is B then $u = p*E + q*\dot{E} + r$
   where E and $\dot{E}$ are the FCS inputs, A and B are fuzzy sets in the antecedent, u is a crisp function in the consequent (in this case a first order polynomial), while p, q, and r are all constants.
2. The FCS rule base consists of four rules:
   R_1: If E is N and $\dot{E}$ is N then $u = p_1*E + q_1*\dot{E} + r_1$
   R_2: If E is N and $\dot{E}$ is P then $u = p_2*E + q_2*\dot{E} + r_2$
   R_3: If E is P and $\dot{E}$ is N then $u = p_3*E + q_3*\dot{E} + r_3$
   R_4: If E is P and $\dot{E}$ is P then u $= p_4*E + q_4*\dot{E} + r_4$
   where the coefficient constants $p_i = q_i = 1$, and $r_i = 0$; for $i = 1, 2, 3, 4$.
3. The universe of discourse for both FCS inputs is normalized on the range [-1, 1].
4. The membership functions of the input variables, E and $\dot{E}$, to the FCS are triangular complementary adjacent fuzzy sets [19], [20], and they are defined as shown in Fig. 4(a). The fuzzy labels means, P = Positive, and N = Negative.

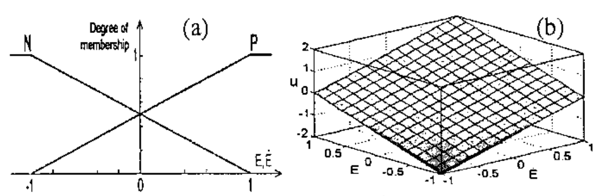

Fig. 4. (a) Membership functions for E and $\dot{E}$, (b) Control surface of the normalized and linear FCS.

5. The product-sum compositional rule of inference [21] is used in the stage of rule evaluation.
6. The weighted average is used in the defuzzification process.

then the FCS output is given by the sum of its inputs. This FCS is normalized and linear [7]-[8], [15], and is the simplest that can be considered inside the MHPID-FLC structure; its control surface is shown in Fig. 4(b).

Thus, the control output u_{PID} of the MHPID-FLC (see Fig. 3) is the sum of the PI-FLC output and the PD-FLC output parts,

$$u_{PID}(t) = u_{PI}(t) + u_{PD}(t) \tag{6}$$

but, under the assumptions made, each part can be written as:

$$\begin{aligned} u_{PI}(t) &= GCU * \int \left(E(t) + \dot{E}(t)\right) * dt \\ &= GCU * \int \left(GE * e(t) - GCE * \frac{dy(t)}{dt} \right) * dt \end{aligned} \tag{7}$$

$$\begin{aligned} u_{PD}(t) &= GU * \left(E(t) + \dot{E}(t)\right) \\ &= GU * \left(GE * e(t) - GCE * \frac{dy(t)}{dt} \right) \end{aligned} \tag{8}$$

Substituting (7) and (8) in (6) results in:

$$\begin{aligned} u_{PID}(t) &= GCU * GE * \int e(t) * dt - GCU * GCE * y(t) \\ &\quad + GU * GE * e(t) - GU * GCE * \frac{dy(t)}{dt} \\ &= GCU * GE * \int e(t) * dt - GCU * GCE * y(t) \\ &\quad + GU * GE * (y_r(t) - y(t)) - GU * GCE * \frac{dy(t)}{dt} \\ &= GU * GE * y_r(t) - (GCU * GCE + GU * GE) * y(t) \\ &\quad + GCU * GE * \int e(t) * dt - GU * GCE * \frac{dy(t)}{dt} \end{aligned} \tag{9}$$

If (9) and (5) are compared, it is noted that the MHPID-FLC controller works like a traditional PID controller with set point weighting factor and modified derivative term. The equivalent set-point weight, proportional, integral and derivative gains are:

$$K_P * \beta = GU * GE \tag{10}$$

$$K_P = GCU * GCE + GU * GE \tag{11}$$

$$K_I = \frac{K_P}{T_i} = GCU * GE \tag{12}$$

$$K_D = K_P * T_d = GU * GCE \tag{13}$$

This means that the SF of the MHPID-FLC can be derived from the proportional, integral and derivative gains obtained for the traditional PID controller using well known methods, i. e. the Ziegler-Nichols method [16]. A procedure for this task is presented in next section.

III. Designing And Tuning Of The MHPID-FLC

If the values of K_P, K_I, and K_D or alternatively the values of K_P, T_i, and T_d are available, then the values of GE, GCE, GU and GCU in the MHPID-FLC structure (see Fig. 3) can be calculated in the following way. The proportional gain given in (11) can be separated in two parts:

$$\begin{aligned} K_P &= GCU * GCE + GU * GE \\ &= \alpha * K_P + (1 - \alpha) * K_P \end{aligned} \tag{14}$$

from here it follows,

$$GCU * GCE = \alpha * K_P \tag{15}$$

$$GU * GE = (1 - \alpha) * K_P \tag{16}$$

From (10) and (16) it can be directly deduced that,

$$\beta = 1 - \alpha \tag{17}$$

From assumption 3 it is clear that the possible values of E are in the range [-1, 1], thus in order to avoid saturation, GE is selected as:

$$GE = 1 \tag{18}$$

In consequence, from (18), (16) becomes,

$$GU = (1 - \alpha) K_P \tag{19}$$

In a similar way, from (18), (12) becomes,

$$GCU = K_I \tag{20}$$

Calculating GCE from (13) gives,

$$GCE = \frac{K_D}{GU} \tag{21a}$$

and from (19) in (21a) gives,

$$GCE = \frac{K_D}{(1 - \alpha) * K_P} \tag{21b}$$

Thus, once the parameter α is defined, the SF can be calculated using Equations (18) to (21). But now the question is how should the parameter α be properly defined? First of all α has to satisfy (15) and (19), thus from (20) and (21b) in (15) gives,

$$K_I * \frac{K_D}{(1 - \alpha) * K_P} = \alpha * K_P \tag{22}$$

and solving (22) for α gives,

$$-\alpha^2 + \alpha = \frac{K_I * K_D}{K_P^2} \tag{23}$$

But, from traditional PID control,

$$K_I = \frac{K_P}{T_i} \quad ; \quad K_D = K_P * T_d \qquad (24).$$

Thus, from (24) in (23) gives,

$$-\alpha^2 + \alpha - \frac{T_d}{T_i} = 0 \qquad (25),$$

and applying the relation between T_i and T_d given by the Ziegler-Nichols frequency response tuning method (see Table I), finally leads to,

$$-\alpha^2 + \alpha - \frac{1}{4} = 0 \qquad (26).$$

Solving equation (26) results in,

$$\alpha_1 = \alpha_2 = \frac{1}{2} \qquad (27).$$

Finally, by substituting the value of α in (19) and (21b), the solutions for GU and GCE become straightforward. The previous development means that the MHPID-FLC is equivalent to its traditional counterpart given by (5) when β is selected as 0.5, calculated from (17), and the Ziegler-Nichols frequency response method is used to tune the controller. The formulation of the SF in function of K_P, T_i, and T_d is straightforward. A summary of the relationship between the SF of the MHPID-FLC and the gains of its traditional counterpart is given in Table II.

TABLE I
PID PARAMETERS ACCORDING TO THE ZIEGLER-NICHOLS FREQUENCY RESPONSE METHOD

K_P	T_i	T_d
$0.6*K_u$	$(1/2)*T_u$	$(1/8)*T_u$

TABLE II
RELATIONSHIP BETWEEN THE SCALING FACTORS OF THE MHPI-FLC AND THE GAINS OF ITS TRADITIONAL COUNTERPART

GE	GCE	GU	GCU
1	$2*\frac{K_D}{K_P}$	$\frac{K_P}{2}$	K_I
1	$2*T_d$	$\frac{K_P}{2}$	$\frac{K_P}{T_i}$

Further, fine-tuning can be made based on the relationship between the SF of the MHPID-FLC and the three control actions of traditional PID control. This fine-tuning, can be developed in two ways: A) by modifying the SF, B) by modifying the control surface of the FCS inside the MHPID-FLC structure. These procedures are described next.

A. Fine-tuning the controller by modifying the SF of the MHPID-FLC

The role of the SF of the MHPID-FLC can be determined by analogy to the gains of the traditional PID controller. Assuming that the value of GE is fixed as 1 and using the information from Table II, general guidelines for fine tuning the SF of the MHPID-FLC can be given. Changing the value of GCU will affect both the proportional control term and the integral control term, see (11) and (12). Thus, increasing the value of GCU will produce a faster but less stable control. The opposite action will cause the opposite effect. Changing the value of GU affects both the proportional control term and the derivative control term, see (11) and (13). Therefore, increasing the value of GU produces both faster and more stable control. But this is only true up to a certain limit, if GU is raised above this limit then it will result in reduced stability in control. Decreasing the value of GU will produce the opposite effect. Finally, a change in the value of GCE will affect both the proportional control term and the derivative control term, see (11) and (13). Therefore, increasing the value of GCE causes a faster and more stable control. But, as for the case of GU, if GCE is raised above of certain limit the system will be destabilized. Additionally, because GCE is an input SF, it has to be manipulated carefully to avoid saturation. It is recommended to first adjust the output SF, and if necessary, adjust GCE afterwards. A summary of the whole analysis is presented in Table III.

TABLE III
EFFECTS OF THE SCALING FACTORS ON SPEED AND STABILITY

	Speed	Stability
GCU increases	increases	reduces
GU increases	increases	increases
GCE increases	increases	increases

B. Fine-tuning the controller by modifying the control surface of the FCS inside the MHPID-FLC structure

The main advantage of considering a first-order Takagi-Sugeno FCS inside the MHPID-FLC structure is that by changing the values of the consequent parameters in the fuzzy rules, *p*, *q* and *r*, the FCS control surface is modified. This means that the strength of the three PID control actions can be regulated changing the FCS control surface without modifying the initially found SF. For example, Fig. 5 shows the FCS control surface obtained with modified consequent parameters: $p_1=p_4=2.5$, $q_1=q_4=3$, $r_1=r_4=0$, $p_2=p_3=0.4$, $q_2=q_3=0.4$, $r_2=r_3=0$. With these consequent parameters the strength of the control action is increased at the extremes, when E and $\dot{E}$ are larger, and reduced when E and $\dot{E}$ are near zero, near the steady state. Additionally, note that the transition between a stronger and a weaker control action is done smoothly. It means that a kind of gain scheduling is obtained. However, the modification of the consequent parameters makes the FCS control surface nonlinear, thus they have to be manipulated carefully.

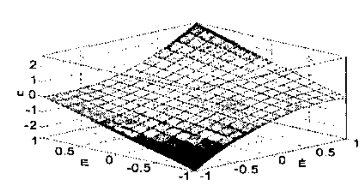

Fig. 5. FCS control surface with modified consequent parameters.

IV. Simulation And Comparisons

In this section the viability of this approach is demonstrated by simulating four benchmark processes taken from the literature [8], [10], [16], [22]. The simulation is developed in Matlab environment together with Simulink and the Fuzzy Logic Toolbox. The fourth-order Runge-Kutta numerical integration method is used with an integration interval of 0.01s. The chosen quantitative criteria for measuring the performance are the well-known integral of absolute error (IAE) and the integral of time absolute error (ITAE). The IAE and ITAE values are measured twice for each process (as is shown in Tables IV to VII). The first values are taken when the process reaches the steady state after a step set-point change has been applied and before a load disturbance is applied. The second values are taken after a load disturbance is applied and the steady state has been reached.

First, for each process the traditional PID controller (from here referred to as TPID) with set point weighting factor of 0.5 and modified derivative term is tuned using the Ziegler-Nichols frequency response method. Secondly, the initial scaling factors for the MHPID-FLC are calculated from the formulae given in Table II. Thirdly, leaving fixed the calculated scaling factors, fine-tuning is developed by modifying the control surface of the FCS inside the MHPID-FLC structure (controller referred to as MHPID-FLC-MCS). Finally, using the linear FCS control surface and starting with the calculated scaling factors, fine-tuning is developed by changing the scaling factors of the MHPID-FLC (controller referred to as HPID-FLC-MSF) following the general guidelines given in Table III.

From Figs. 6 to 9 and Tables IV to VII it can be noted that both the TPID and the MHPID-FLC have similar performance for all processes. In fact, the difference is only noticeable through the IAE and ITAE values. As well it can be noted that by modifying the scaling factors only the set-point response is improved for processes G_1 to G_3. However, in process G_4 both set-point and load disturbance responses are improved. It is remarkable to note that for all processes the performance in both set-point and load disturbance responses are significantly improved by modifying the FCS control surface.

The simulated processes, the IAE and ITAE values, and the comparison of the set-point and load-disturbance responses obtained applying each one of the controllers, above referred, are presented next.

1) Second-order process: $$G_1(s) = \frac{e^{-0.4s}}{(s+1)^2} \tag{28}$$

TABLE IV
PERFORMANCE OF CONTROLLERS FOR PROCEES $G_1(s)$

Process $G_1(s)$	t=10s		t=20s	
Controller	IAE	ITAE	IAE	ITAE
TPID	1.4608	1.4580	1.9421	7.2679
MHPID-FLC	1.4627	1.4666	1.9448	7.2887
MHPID-FLC-MCS	1.2533	1.0850	1.5630	4.7781
MHPID-FLC-MSF	1.3496	1.0626	1.9051	7.8865

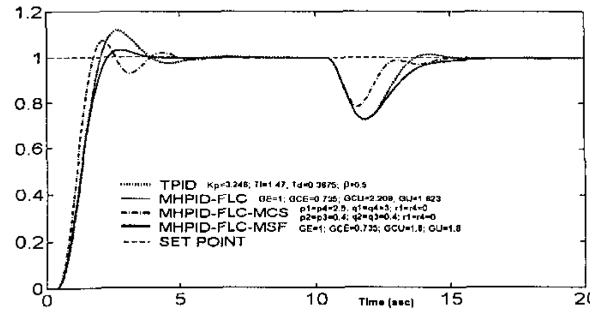

Fig. 6. Set-point and load-disturbance responses for process $G_1(s)$.

2) Third-order process: $$G_2(s) = \frac{1}{(s+1)^3} \tag{29}$$

TABLE V
PERFORMANCE OF CONTROLLERS FOR PROCEES $G_2(S)$

Process $G_2(s)$	t=20s		t=40s	
Controller	IAE	ITAE	IAE	ITAE
TPID	1.7775	3.2937	2.1682	12.2621
MHPID-FLC	1.7826	3.3286	2.1747	12.3358
MHPID-FLC-MCS	1.3954	1.8447	1.5923	6.2483
MHPID-FLC-MSF	1.4478	1.4914	1.9023	11.9162

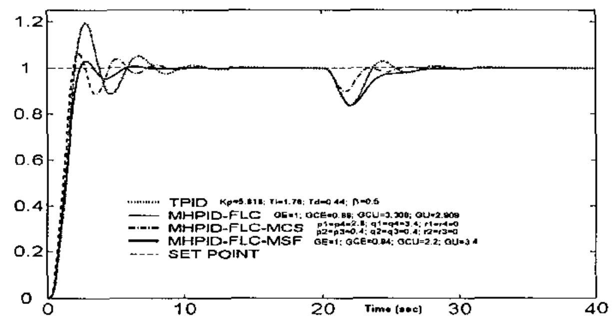

Fig. 7. Set-point and load-disturbance responses for process $G_2(s)$.

3) Fourth-order process: $$G_3(s) = \frac{27}{(s+1)(s+3)^3} \tag{30}$$

TABLE VI
PERFORMANCE OF CONTROLLERS FOR PROCEES $G_3(S)$

Process $G_3(s)$	t=10s		t=20s	
Controller	IAE	ITAE	IAE	ITAE
TPID	1.3033	1.2473	1.7523	6.6022
MHPID-FLC	1.3057	1.2575	1.7557	6.6282
MHPID-FLC-MCS	1.2356	1.1839	1.5992	5.5179
MHPID-FLC-MSF	1.1982	1.0363	1.6246	6.1383

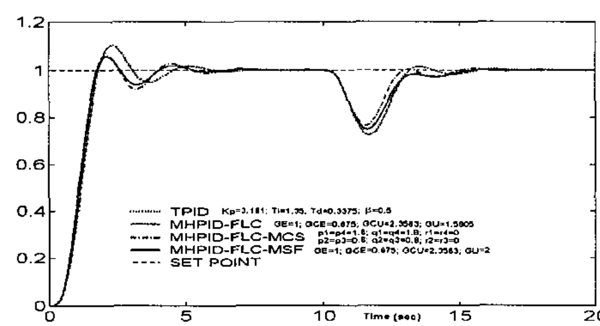

Fig. 8. Set-point and load-disturbance responses for process $G_3(s)$.

4) Non-minimum phase process: $G_4(s) = \dfrac{1-1.4s}{(s+1)^3}$ (31)

TABLE VII
PERFORMANCE OF CONTROLLERS FOR PROCEES $G_4(s)$

Process $G_4(s)$	t=40s		t=80s	
Controller	IAE	ITAE	IAE	ITAE
TPID	6.0283	25.3271	10.8501	251.9347
MHPID-FLC	6.2119	26.6769	11.0336	253.2811
MHPID-FLC-MCS	4.0518	9.4458	7.8255	181.8579
MHPID-FLC-MSF	4.6542	12.5314	8.4047	182.9612

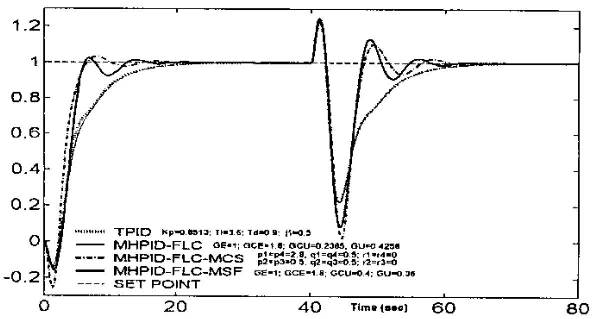

Fig. 9. Set-point and load-disturbance responses for process $G_4(s)$.

V. CONCLUSIONS

A new methodology for designing and tuning the scaling factors of a modified hybrid PID type fuzzy logic controller (MHPID-FLC) has been presented. First, a direct relationship between the scaling factors of the MHPID-FLC and the proportional, integral and derivative actions of its traditional counterpart has been derived. Second, based on this relationship, the scaling factors are obtained using the well-known Ziegler-Nichols frequency response method. A remarkable point is that based on this relationship, the auto-tuning algorithm proposed by Astrom and Hagglund [23] can be extended and developed for applications to the tuning of the scaling factors of the MHPID-FLC [24].

General guidelines for fine tuning and further improving the performance of the MHPID-FLC were given. It has been shown that this fine-tuning can be carried out in two ways: 1) modifying the scaling factors, 2) modifying the control surface of the fuzzy control system inside the HPID-FLC structure.

The proposed methodology was tested in several simulated benchmark processes. In all cases the performance of the MHPID-FLC is improved by modifying the scaling factors or by modifying the FCS control surface inside the MHPID-FLC structure. From here it may be deduced that the apparent disadvantage of the MHPID-FLC of having coupled its controller parameters appears to be an advantage when they are manipulated carefully and considering their effect on the three PID control actions. However, more research on the effects of fine-tuning the MHPID-FLC by modifying the FCS control surface is needed, in fact it opens an avenue of investigation that is being explored by the authors.

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