Fuzzy Model Reference Adaptive Control Based on PID for Fundamental and Typical Industrial Plants

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***Abstract* - This paper presents a model reference tracking based PID controller with adaptive procedure to improve the regulation precision and dynamic response of the typical closed-loop systems. The proposed control structure consists of two main parts that cooperate with each other. A PID controller is first designed to stabilize and provide nominal system control and a fuzzy logic controller that enhances tracking ability and robustness to the system uncertainties. The effectiveness of the proposed algorithm is validated through its applications in some fundamental industrial processes. Since there is no plant identification phase, it has an easy on-line implementation and a real-time performance.**

Keywords- Model reference adaptive control; robustness; Fuzzy control; tuning PID methods

I. INTRODUCTION

Industrial process plants often contain nonlinearities and variations due to the plant nature, noise, disturbances and other environmental conditions. Usually, nonlinearities may have undesirable effects. Thus, control design may need to properly compensate those effects, or to linearize nonlinear terms. Nonlinearities can be classified in terms of their mathematical properties, as continuous and discontinuous [1]. In substance, continuous nonlinearities can be linearized, but discontinuous nonlinearities can't be locally approximated by linear functions. They are also called "hard" nonlinearities [1]. Unfortunately, in practice, most of systems have hard nonlinearities, such as backlash, hysteresis and stiction. Thus, nonlinear control design is an issue for common systems.

PID control techniques have been applied widely in industry because of their simple structure, good stable performance and high reliability. In general, PID controls are used for steady-state tracking of step inputs or slow time-varying reference trajectories. However, PID controls are not robust against system uncertainties and external disturbances because the proportional and derivative coefficients are usually fixed. Tuning a set of satisfied control parameters is crucial. For this reason, various tuning methods have been investigated in the literature. Several tuning methods has been compared in [1, 2]. To improve system performance and enhance system robustness of PID control, adaptive algorithms and self-learning rules need to be developed. Without adaptively tuning the PID parameters, the system performances will be sensitive to system operating condition and parameter variations [3]. By identifying the plant parameters and tuning control parameters, the adaptive controller can adaptively change the control parameters.

Model reference adaptive control (MRAC) system is a kind of very important adaptive system [4]. The general idea behind Model Reference Adaptive Control (MRAC) is to create a closed loop controller with parameters that can be updated to change the response of the system. Fuzzy set theory has been successfully employed in a variety of fields in recent years. The fuzzy controller essentially is a kind of non-linear controller, the fuzzy control algorithms are built up based on intuition and experience about the plant to be controlled. Therefore, it does not rely on the precise mathematical model, and it is robust with regard to parameter variations [7-14]. In our study, the concept of fuzzy is incorporated into PID controller to design an updating law for MRAC systems. We call this strategy "Fuzzy Model Reference Adaptive Control-Based PID" (FMRAC-PID).This controller combines the benefits of model reference adaptive, PID and fuzzy control. The PID controller is designed to first stabilize the states of the control system. In this stage, the robustness and tracking capability are not sufficiently satisfied. We further design a fuzzy logic controller to complete satisfactory tracking performance and improve regulation precision and robustness of the closed loop system. Moreover, the proposed method need not identify the parameters of the plant. It has a very good real-time performance, and is easy to be implemented on line.

This paper is organized as the following sections: Section II presents the configuration and design procedure. In Section III, the fuzzy logic controller principle is introduced. The performance and robustness of our method is evaluated and compared with other methods in Section IV. Finally, a detailed discussion and conclusion with some remarks are provided in Sections V and VI.

II. FORMULATION OF THE SYSTEM

Structure of the FMRAC-PID controller proposed in this paper is shown in Fig. 1, which is composed of a reference model, a controlled subsystem and a fuzzy control subsystem. The reference model is $M(s)$ whose output $Y_m(s)$ described as desired output with ideal dynamic character and high regulation.

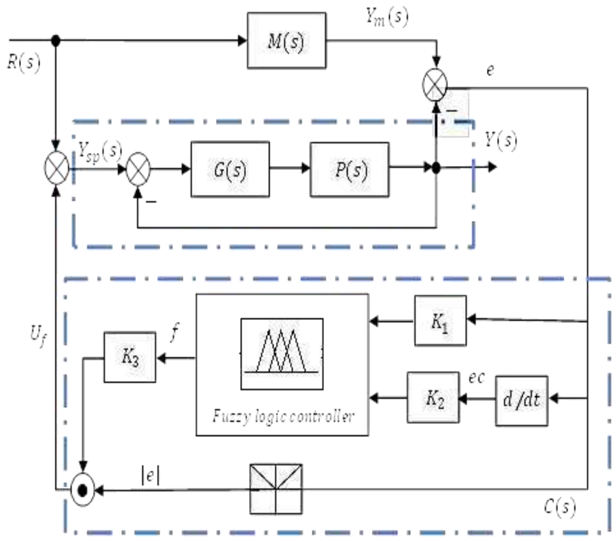

Fig. 1 Block diagram of FMRAC- PID control system

The closed loop controlled subsystem consists of a classical PID control ($G(s)$) and the plant ($P(s)$). The error between reference and actual behavior send to the fuzzy subsystem ($c(s)$). The behavior of the fuzzy controller can then be described in terms of a three–dimensional surface, the dimensions being $e, ec,$ and f. This control surface will serve as a rule surface. The output of the fuzzy control subsystem (U_f) that derived by the current plant response to match the response of the reference model.

The required steps for this arithmetic are:

First, selecting the reference model $M(s)$. The reference output ($Y_m(s)$) should have an ideal dynamic character. The configuration of $M(s)$ can be descried by:

$$M(s) = \frac{1}{Ts+1} \cdot \tag{1}$$

Second, tuning PID controller coefficients for the plant. There are several tuning formulae that meet different requirements. We can tune the PID in a way that minimize the integrated absolute error (IAE), ITAE or ITSE.

$$IAE = \int_0^\infty \left| y_{sp}(t) - y(t) \right| dt \tag{2}$$

$$ITAE = \int_0^\infty \left| y_{sp}(t) - y(t) \right| t dt \tag{3}$$

$$ITSE = \int_0^\infty (y_{sp}(t) - y(t))^2 t dt \tag{4}$$

Third. Design fuzzy controller (Design procedure is explained in the next part).

III. Fuzzy Controller structure

The first step for making a rule set is to find the relation between e, ac and f. Regarding to the current e, ec and rule set, f can be changed on-line. The output U_f of the fuzzy subsystem is calculated by

$$U_f = K_3 . f . |e|. \tag{5}$$

e and ec are scaled to be in the range [-6, 6] where K_1 and K_2 are scaling coefficients. The membership functions are defined by seven triangular membership functions for both input and output variables (see Fig 2, 3). Also, the membership functions for the output (f) are bounded between [-1, 1], which is scaled by K_3 . The following subsets are assigned for the input and output variables:

{NB、NM、NS、Z、PS、PM、PB};

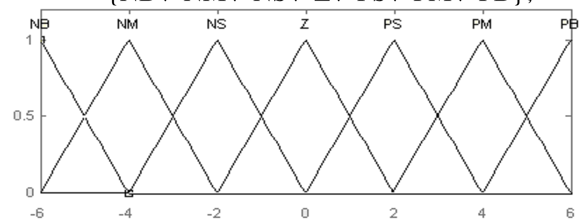

Fig.2 Membership degree for e、ec

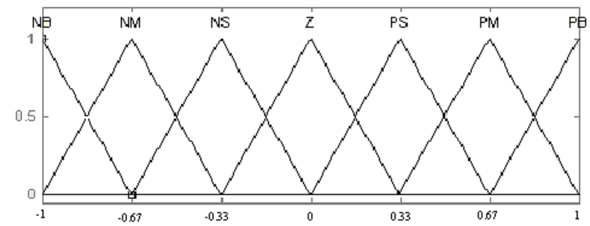

Fig.3 Membership degree for f

The fuzzy inference rules are found in the condition form of "If A and B then C". The relation between the plant and reference model illustrated in Fig. 4. Current error and its difference with the former make one of the following conditions (Fig. 4). As a result, the fuzzy subsystem can give an adaptive corrective signal to the controlled subsystem, in order to decrease error as soon as possible.

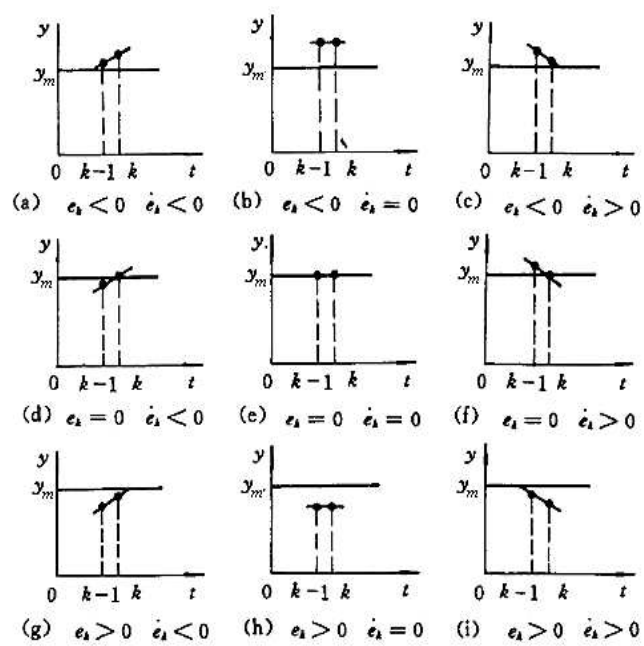

Fig.4 Relations between reference model and plant output

For example, in the first instance, the corrective control effort should be increased rapidly to prevent overshoot. Hence, the fuzzy controller subsystem works as an extra degree of freedom that improves the system dynamics performance. For another example, in the third instance, the corrective control effort should be reduced. This will avoid the outputs deviate from the set-point and will reduce settling time. Here there is no need to fuzzy subsystem as an extra controller. The corresponding rule set of the fuzzy controller is designed in table 1. The surface is depicted in Fig.5.

TAB. I
FUZZY RULE TABLE

ec	*e*						
	NB	NM	NS	Z	PS	PM	PB
PB	Z	Z	Z	PS	PM	PB	PB
PM	NS	Z	Z	PS	PM	PB	PB
PS	NM	NS	Z	Z	Z	PM	PB
Z	NB	NS	Z	Z	Z	PS	PB
NS	NB	NM	NS	Z	Z	PS	PM
NM	NB	NB	NM	NS	Z	Z	PS
NB	NB	NB	NM	NS	Z	Z	Z

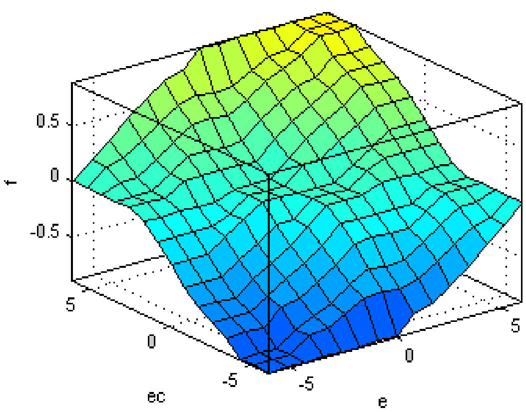

Fig. 5 Rule surface of the fuzzy controller

IV. CONTROL PERFORMANCE

Four groups of fundamental industrial plants were used to evaluate the effectiveness of the methodology.

$$G_1(s)=\frac{K}{Ts+1}e^{-Ls} \tag{6}$$

$$G_2(s)=\frac{K}{s(Ts+1)}e^{-Ls} \tag{7}$$

$$G_3(s)=\frac{K}{Ts-1}e^{-Ls} \tag{8}$$

$$G_4(s)=\frac{K}{s^2+2\zeta\omega_n s+\omega_n^2}e^{-Ls} \tag{9}$$

Experiment 1. first-order plus dead-time process

$$G_1(s)=\frac{1}{s+1}e^{-0.5s} \tag{10}$$

The process starts with describing reference model:

$$M(s)=\frac{1}{0.05s+1}\,. \tag{11}$$

Whose step response is

$$y(t)=1-e^{-\frac{t}{0.05}}\,. \tag{12}$$

Good performance will be obtained with no overshoot and little settling time. At the second stage the PID parameters are adjusted in order to minimize the integrated absolute error multiplied by time (ITAE). $K_p=1.8545$, $K_i=1.3465$, $K_d=0.4332$ and the scaling coefficients are selected as follows: $K_1=70$, $K_2=0.001$, $K_3=-1$. The unit step responses of four different tuning PID methods are compared in Fig.6 (Ziegler–Nichols method, IMC, Jin [2] and FMRAC-PID). With the same settling time, FMRAC-PID scheme has no overshoot. The robustness of the proposed controller was verified for 18% increasing in delay time. It appears that FMRAC-PID has higher robustness than the others (Fig.7).

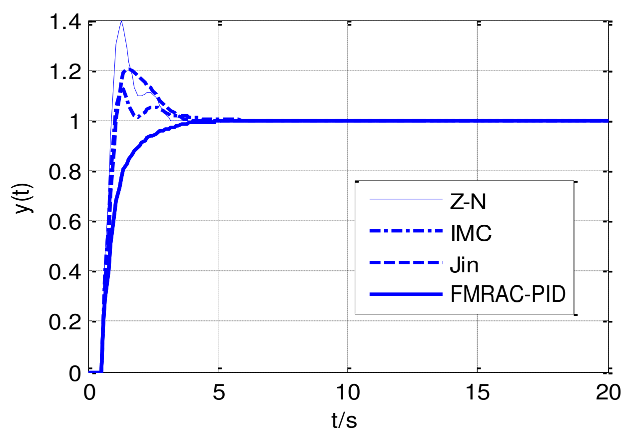

Fig.6. Step response of experiment 1 at nominal case

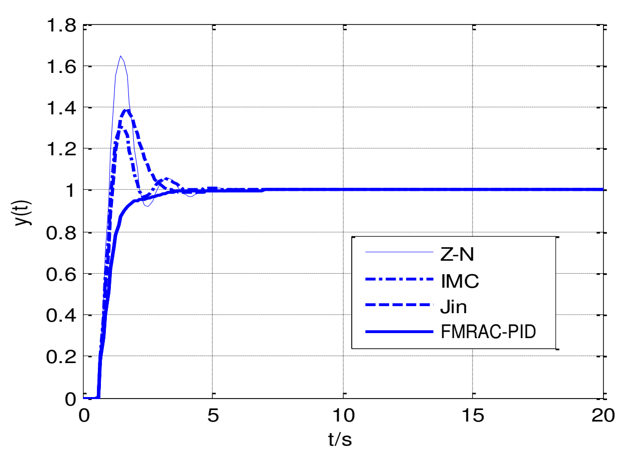

Fig.7. Step response of experiment 1 at the parameter variation case

Experiment 2. integrating plus dead-time process

$$G_2(s) = \frac{1}{s(s+1)} e^{-0.2s} \tag{13}$$

The reference model is selected the same as experiment 1 described by (11). The PID parameters are tuned by (3) are as follows: K_p = 11.54795, K_i = 12.3657, K_d = 4.9632. the scaling coefficients K_1, K_2 and K_3 don't have changed from the previous experiment. The unit step responses of Jin[2] , Poulin and FMRAC-PID scheme are plotted in Fig.8. The FMRAC-PID has smaller overshoot and settling time than others. The robustness was tested for 15% increasing in delay time. Looking at the results in Fig.9, the robustness of FMRAC-PID is better than the other methods.

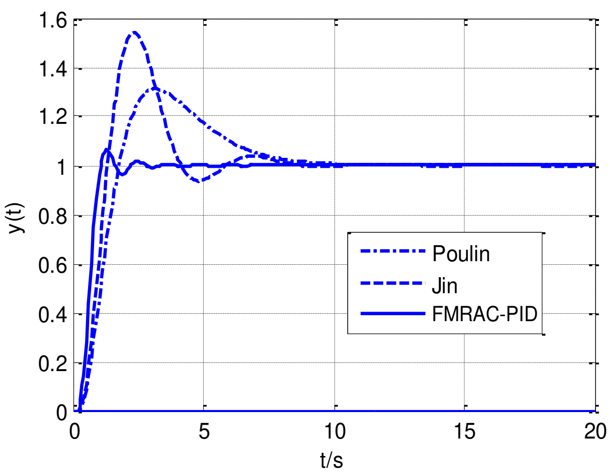

Fig.8. Step response of experiment 2 at nominal case

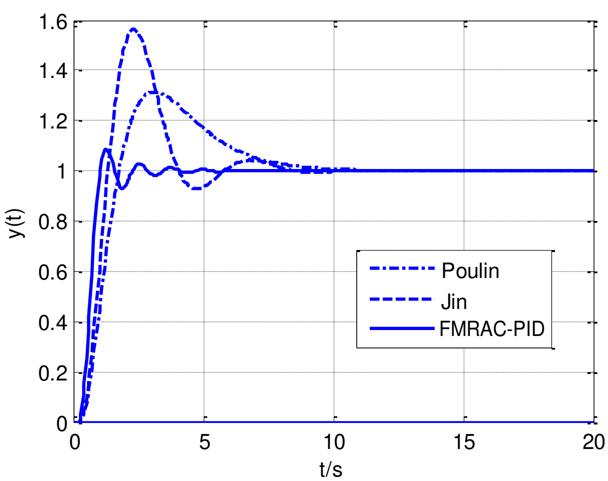

Fig.9. Step response of experiment 2 at the parameter variations case

Experiment 3. first-order delayed unstable process

$$G_3(s) = \frac{1}{s-1} e^{-0.2s} \tag{14}$$

The reference model and scaling coefficients K_1, K_2 and K_3 are selected the same as experiments 1 and 2. The PID parameters that are tuned by (4) are: K_p = 7.0802, K_i = 7.15, K_d = 0.71042. The step response or performance of FMRAC-PID compared with several other methods in Fig.10. Obviously the result of FMRAC-PID is better than the others. For robustness verification, suppose the dead-time is added by +15%. The visioli method step response is emanative (Fig.11). Again FMRAC-PID has a good response.

Load attenuation capability is another controlling factor that investigated for the proposed method. A load disturbance step has been applied to the plant at steady-state initial conditions. From this viewpoint, FMRAC-PID scheme is better than the others. It appears that adaptation in nonlinear conditions provided by fuzzy controller could improve the load attenuation capability and robustness, as well as the dynamic responses of the PID controller.

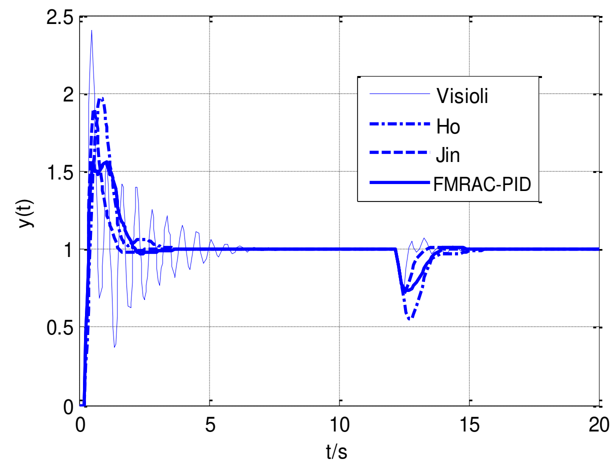

Fig.10. Step response of experiment 3 at nominal case

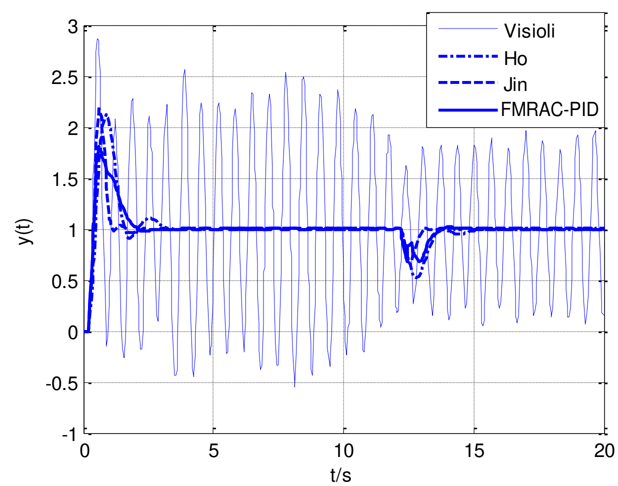

Fig.11. Step response of experiment 3 at the parameter variation case

Experiment 4. second-order plus dead-time process

$$G_4(s) = \frac{0.25}{1.036s^2 + 1.21s + 1} e^{-1.01s} \tag{15}$$

The reference model and scaling coefficients K_1, K_2 and K_3 are the same as former experiments. The PID parameters which are tuned by (4) are as follows: K_p = 4.2152, K_i = 1.6837, K_d = 3.5773. Fig.12 shows that the performance of FMRAC-PID is better than the other methods. The robustness of our method is then tested for 20% increasing of dead-time

(Fig.13). Also, the load attenuation capabilities are verified by a load disturbance step at steady state. Again the FMRAC-PID schemes better or at least equals to the others.

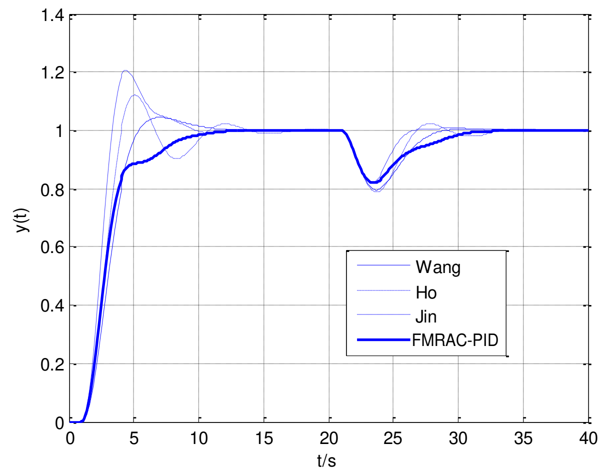

Fig.12. Step response of experiment 4 at nominal case

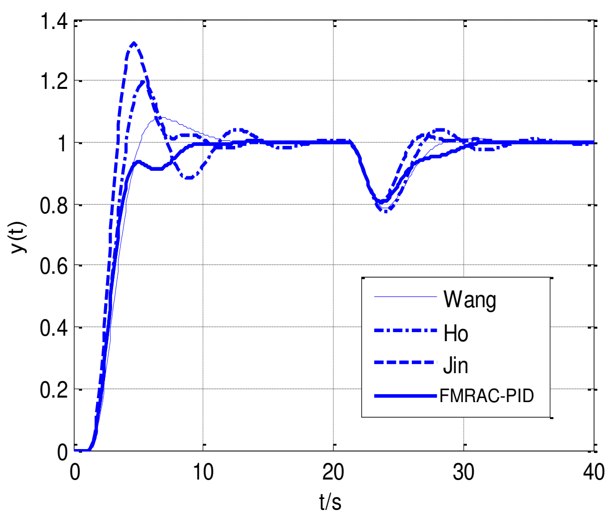

Fig.13. Step response of experiment 4 at the parameter variation case

Overall experimental results are listed in some comparison tables. These comparisons include the values of overshoot, and the values of settle time for nominal and parameter variation cases.

TABLE II
VALUE OF OVERSHOOT (%) FOR FMRAC-PID AND SEVERAL OTHER TUNING METHODS AT NOMINAL CASE

Process	Z-N	Jin	IMC	Poulin	Ho	Visioli	Wang	FMRAC-PID
$G_1(s)$	41	20	16	—	—	—	—	0
$G_2(s)$	—	57	—	33	—	—	—	12
$G_3(s)$	—	85	—	—	90	146	—	58
$G_4(s)$	—	0	—	—	21	—	17	4

TABLE III
VALUE OF OVERSHOOT (%) FOR FMRAC-PID AND SEVERAL OTHER METHODS AT PARAMETER VARIATION CASE

Process	Z-N	Jin	IMC	Poulin	Ho	Visioli	Wang	FMRAC-PID
$G_1(s)$	63	30	31	—	—	—	—	0
$G_2(s)$	—	56	—	32	—	—	—	9
$G_3(s)$	—	83	—	—	95	135	—	61
$G_4(s)$	—	0	—	—	19	—	16	10

TABLE IV
VALUE OF SETTLING TIME (IN SECONDS) FOR FMRAC-PID AND SEVERAL OTHER METHODS AT NOMINAL CASE

Process	Z-N	Jin	IMC	Poulin	Ho	Visioli	Wang	FMRAC-PID
$G_1(s)$	3.2	4.0	3.8	—	—	—	—	3.8
$G_2(s)$	—	7.7	—	9.0	—	—	—	2.1
$G_3(s)$	—	1.9	—	—	3.0	6.5	—	2.0
$G_4(s)$	—	10	—	—	9.0	—	13	9.0

TABLE V
VALUE OF SETTLING TIME (IN SECONDS) FOR FMRAC-PID AND SEVERAL METHODS AT PARAMETER VARIATION CASE

Process	Z-N	Jin	IMC	Poulin	Ho	Visioli	Wang	FMRAC-PID
$G_1(s)$	4.6	3.0	4.0	—	—	—	—	3.0
$G_2(s)$	—	7.5	—	8.7	—	—	—	4.0
$G_3(s)$	—	1.0	—	—	2.8	---	—	1.6
$G_4(s)$	—	13	—	—	18	—	12.0	9.0

V. DISCUSSION

The combination of fuzzy and PID control in a model reference structure has made an adaptive tuning algorithm that improves the step response dynamic performances and robustness to the plant parameter variations. The application of the proposed methodology is further simplified, since no great attention has to be paid in the initial tuning phase. This implies that the control system will be stable and robust even when the PID controller is not well designed. Also, there is no need to identify the parameters of the controlled plant. Thus, it has a very good real-time performance, and is easy to be implemented on line.

The future work will be focus on using a fuzzy cerebellar model articulation controller (FCMAC) as the fuzzy logic controller of the proposed structure. FCMAC is one of the robotic controllers that inspired from the cerebellar motor control function and used to produce smooth, coordinated movements. We intend to evaluate the ability of FMRAC-PID with a fuzzy CMAC subsystem in robotic motion control.

V. CONCLUSION

A novel method based on adaptive control, fuzzy control and PID control has been proposed for designing a robust control system with good dynamic character and high regulation precision. The approach has been very effective in the set-point following for a large number of industrial processes. Step response gives lower overshoot and less settle time. The performance is insensitive to parametric variations of the system, whilst the PID controller high regulation and load disturbance attenuation are preserved or improved. The devised control structure can be easily adopted in industrial settings, since it requires a small computational effort and easy tuning.

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