International Conference on Automation and Logistics
Qingdao, China September 2008

Model Reference Fuzzy Adaptive PID Control and Its Applications in Typical Industrial Processes

Yan-qing Peng[1,2], Jian Luo[1*], Jin-fa Zhuang[1] and Chang-qing Wu[1]

1. Department of Automation
Xiamen University
Xiamen 361005, China

2. Department of Electronic and Electrical Engineering
Xiamen University of Technology
Xiamen 361005, China

* jianluo@xmu.edu.cn

***Abstract* - To improve the dynamic response, regulation precision and robustness of the closed-loop system, a novel two degree of freedom control method called model reference fuzzy adaptive PID (MRFA-PID) control is proposed for industrial processes. The proposed control law consists of two parts, PID controller and fuzzy logic controller. The PID controller，which is designed for the nominal plant, guarantees the basic requirement on stability and product quality. The fuzzy logic controller, as an extra degree of freedom, improves the system dynamic performance, regulation precision, and robustness to the uncertainty of the system. The effectiveness of MRFA-PID control is illustrated by its applications in some typical industrial processes. Since the proposed method need not identify the uncertain parameters of the plant, it has a very good real-time performance, and is easy to be implemented on-line.**

Index Terms - Model reference adaptive control; Fuzzy control; PID control; robustness

I. INTRODUCTION

Industrial process control systems have some general significant features such as high-order, nonlinearities, time delay, etc. Their performance can be affected by noises, load disturbances and other environmental conditions that cause parameter variations or sudden modifications of the model structure. Thus, it is an urgent requirement to design a robust controller with good dynamic response and high regulation precision. PID control techniques are widely used in industrial process control. The PID controller has simply structure, good stable performance and high reliability. How to tune a set of satisfied control parameters is a crucial issue. For this reason, many tuning formulae have been proposed in the literature. They meet different requirements such as set-point following, attenuation of load disturbance, rejection of noise, and so on, please refer to [1] and the references in it for details. Jin has compared several tuning methods in [2]. However, PID controller is designed based on the nominal model of the process. Without adaptively tuning the parameters of the PID controllers, the system performances will be sensitive to system operating condition and parameter variations [3].

The adaptive control is mainly used to handle the control problems with varying process parameters, which are difficult to be solved by using traditional methods. By identifying the process parameters and tuning control parameters, the adaptive controller can adapt the change of the controlled process parameters. Model reference adaptive control (MRAC) system is a kind of very important adaptive system [4]. A common and parameter-dependent Lyapunov functions which can be computed in some cases via LMI to deal with the uncertainty was introduced in [5-7].

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 [8-20]. To tackle the difficulty of designing the updating law for MRAC systems, this paper proposed a novel method, named model reference fuzzy adaptive PID (MRFA-PID) control. Compared with fuzzy PID controller and other adaptive controllers, MRFA-PID controller combines the benefits of PID control, model reference adaptive control and fuzzy control. The proposed controller has a two degree of freedom configuration. Specifically, the controller consists of two parts, PID controller and fuzzy logic controller. The PID controller is designed for the nominal plant. The fuzzy logic controller is designed to improve the dynamic response, regulation precision and robustness of the closed-loop system. As a result, this controller has high robustness with respect to parameter variations, as well as good dynamic character and high product quality. 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.

The paper is organized as follows. Section II presents the configuration of the proposed controller and the design procedure. In Section III, the principle of fuzzy logic controller design is introduced. The applications of our method in some typical industrial processes are presented in Section IV, while a detailed discussion is provided in Section V. Finally, we conclude the paper with some remarks in Section VI.

II. MODEL REFERENCE FUZZY ADAPTIVE PID CONTROL

The configuration of the model reference fuzzy adaptive PID controller proposed in this paper is shown in Fig. 1, which is composed of a controlled subsystem, a reference model subsystem and a fuzzy control subsystem. The controlled subsystem is a closed-loop subsystem based on classical PID control, $P(s)$ is the plant and $G(s)$ is the PID controller. The reference model subsystem constitutes of $M(s)$,

978-1-4244-2503-7/08/$20.00 © 2008 IEEE

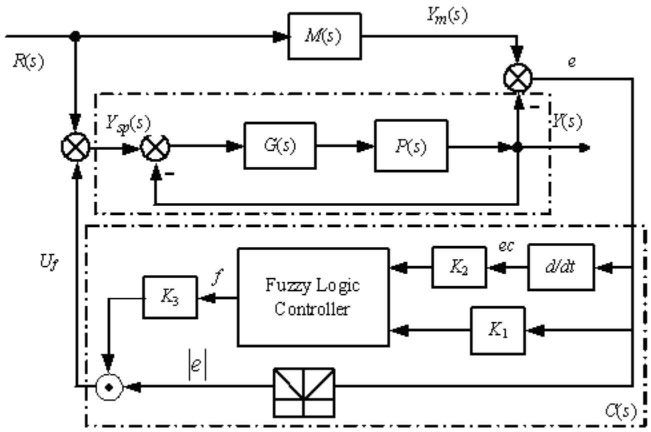

Fig. 1 Block diagram of MRFA- PID control system

whose output $Y_m(s)$ can reach all control targets with ideal dynamic character and high regulation. The fuzzy control subsystem $C(s)$ output U_f is driven by the current error and its time derivative between the outputs of controlled subsystem and reference model, which makes the output of the controlled subsystem follows the output of the reference model subsystem as soon as possible.

This arithmetic needs three steps as follows:

Firstly, select the reference model $M(s)$, whose output $Y_m(s)$ should have ideal dynamic character and high regulation. The configuration of the reference model can be described by:

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

Secondly, tune PID controller parameters for the plant. Many tuning formulae have been proposed in the literature [1-2] and they meet different requirements such as set-point following, attenuation of load disturbance, rejection of noise, and so on. We can tune PID controller parameters in order to minimize the value of the integrated absolute error (IAE), ITAE or ITSE.

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

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

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

Finally, design fuzzy control subsystem. The particulars of the method are shown in part III.

III. DESIGN OF THE FUZZY CONTROLLER

Taking e and ec as the input variables, f as the output variable, The realization thought is as follows: Firstly, the fuzzy relations between e , ec and f should be founded. Then f can be changed on-line, according to the rules, current e and ec. Thus good dynamic performances can be get. The output U_f of the fuzzy control subsystem is given by

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

The two inputs of the fuzzy inference system, the error e and its derivative ec are scaled by two coefficients, K_1 and K_2, respectively, in order to match the range [-6，6] on which the membership functions are defined. Seven triangular membership functions (see Fig.2) are defined for each input while seven triangular membership functions (see Fig.3) over the range [-1，1] are defined for the output, which is scaled by a coefficient K_3. The following seven fuzzy subsets are assigned for input variables e and ec as well as the output variable f:

{NB、NM、NS、Z、PS、PM、PB}；

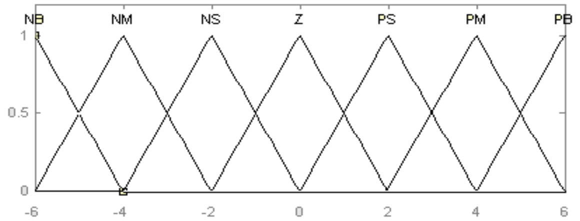

Fig.2 Membership degree of e、ec

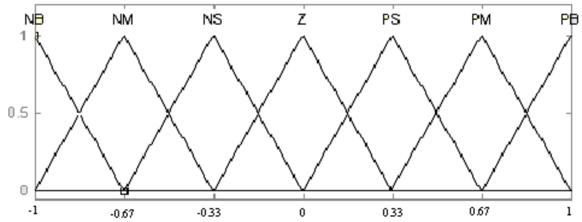

Fig.3 Membership degree of f

The fuzzy inference rules are found according to general fuzzy conditions and fuzzy relations in the form of "If A and B then C". The outputs relations between the plant and reference model are shown in Fig. 4. The basic rules of design fuzzy inference rules are as follows: If we get the sampling value of this moment and the former moment of $y(t)$ depart from $y_m(t)$, according to which, the fuzzy inference subsystem can give a fuzzy adaptive signal value to the controlled subsystem, in order to drive $y(t)$ tracking $y_m(t)$ as soon as possible.

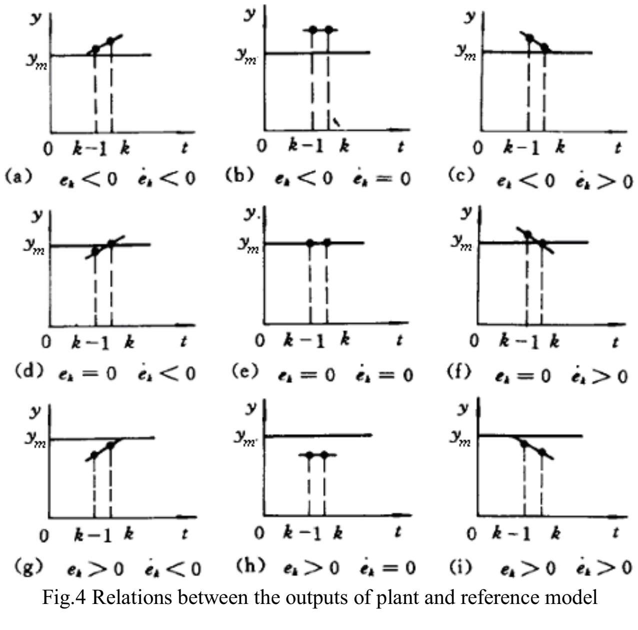

Fig.4 Relations between the outputs of plant and reference model

For example, for the first instance, the control degree should be increased rapidly in order to prevent $y(t)$ from departing from $y_m(t)$, as to reduce the overshoot. When the third instance occurs, the control degree should be reduced, which can avoid the outputs deviate the set-point again after reaching it, so the settling time can be reduced effectively.

Based on above thoughts, the rule bases for fuzzy controller are designed in Table I. The corresponding surface is depicted in Fig.5. The defuzzification method is centroid.

IV. APPLICATIONS

Four groups of typical industrial processes, first-order plus dead-time processes, integrating plus dead-time processes, first-order delayed unstable processes and second-order plus dead-time processes, have been chosen in order to test the effectiveness of the methodology. The following transfer functions have been considered [2]:

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

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

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

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

TAB. I

FUZZY CONTROL RULE TABLE

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

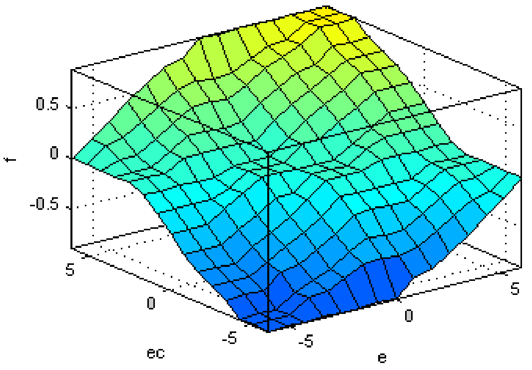

Fig. 5 Rule surface viewer of the fuzzy controller

The unit step response was simulated with Matlab and simulink for all the processes. Plots of the step responses in the three or four cases are reported in Figs.6-13 only for few plants, for the sake of brevity.

Example 1 first-order plus dead-time process

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

According to the procedure described in Section III, firstly, selecting reference model $M(s)$, which is described by:

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

Whose step response is described by

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

Good dynamic performance can be obtained with no overshoot and little settling time.

Secondly, the PID controller parameters are tuned in order to minimize the value of the integrated absolute error multiplied by time (ITAE). The PID controller parameters which are tuned by (3) are as follows: K_p = 1.8232, K_i = 1.2543, K_d = 0.32253.

The coefficients K_1, K_2 and K_3, which are defined for scaling the input and output variables of fuzzy inference system, are selected as follows: K_1 = 60, K_2 = 0.001, K_3 = -1. Plots of the unit step responses in four cases, classical Ziegler–Nichols method, IMC, Jin[2] and MRFA-PID scheme are reported in Fig. 6. It is obvious, looking at the results, that the value of overshoot is zero for MRFA-PID scheme whilst the settle time does not increase. So the MRFA-PID has better dynamic performances than others.

In order to verify the robustness of the proposed controller, on the assumption that the delay-time is increased by 20%, plots of the step response are shown in Fig.7. From the results, it appears that, the MRFA-PID has higher robustness than the others.

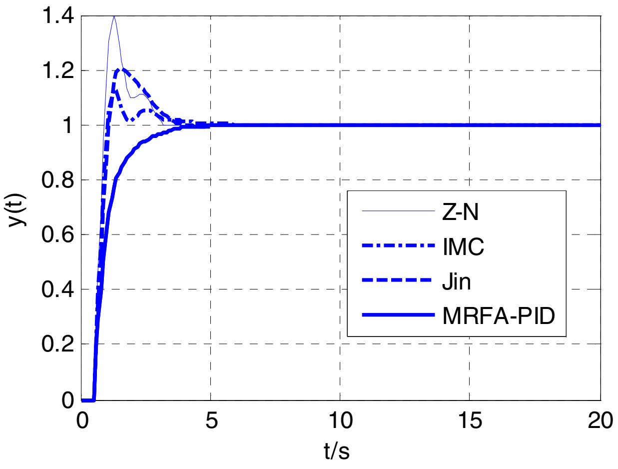

Fig.6. Step response for $G_1(s)$ at nominal case

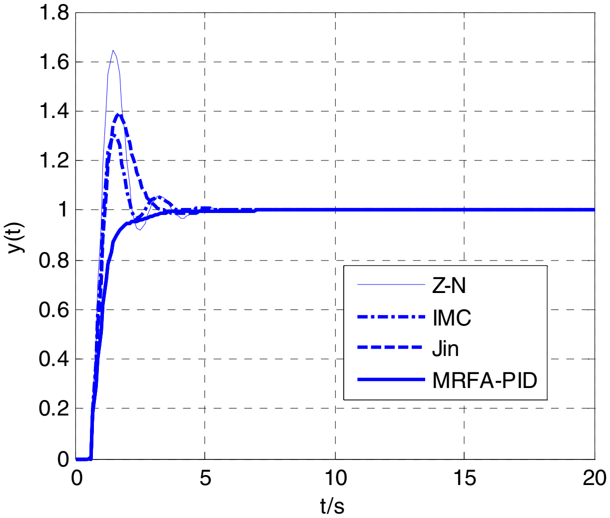

Fig.7. Step response for $G_1(s)$ at the parameter variation case

Example 2 integrating plus dead-time processe666

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

Firstly, select the reference model $M(s)$, which is the same as the model described by (11). Secondly, the PID controller parameters are tuned in order to minimize the value of the integrated absolute error multiplied by time (ITAE). The PID controller parameters which are tuned by (3) are as follows: $K_p = 10.53665$, $K_i = 11.5437$, $K_d = 3.9526$.

The coefficients K_1, K_2 and K_3, which are the same as selected in example 1. Plots of the unit step responses in three cases, Poulin, Jin[2] and MRFA-PID scheme are reported in Fig. 8. It is obvious, looking at the results, that the value of overshoot and settle time both are smaller for MRFA-PID than others. Plots of the step response at the case of the delay-time increases 10% are shown in Fig.9. The results show that the MRFA-PID has better robustness than the other methods.

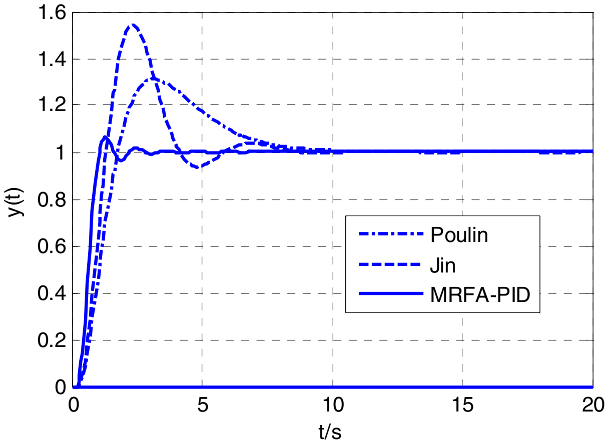

Fig.8. Step response for $G_2(s)$ at nominal case

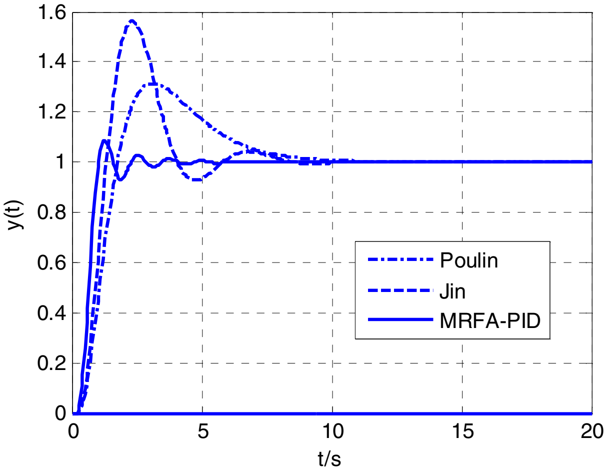

Fig.9. Step response for $G_2(s)$ at the parameter variations case

Example 3 first-order delayed unstable process

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

The reference model $M(s)$ is the same as designed in examples 1 and 2. The PID controller parameters which are tuned by (4) are as follows: $K_p = 6.0702$, $K_i = 6.14$, $K_d = 0.60041$. The coefficients K_1, K_2 and K_3, which are the same as selected in examples 1 and 2.

The step responses for several methods are reported in Fig.10. Obviously, the performance of MRFA-PID is better than the others and the output of Visioli method oscillate excessively. In order to verify the robustness, suppose the dead-time is added by +10%, Fig.11 shows the step responses at parameter variation case. The output of Visioli method is emanative. The results show that the MRFA-PID has better robustness than the other methods.

In order to verify the load attenuation capabilities of the proposed controller, a load disturbance step has been applied to the plant at steady-state initial conditions. From the load-disturbance attenuation viewpoint, again, the MRFA-PID scheme is better than the others. It appears the nonlinearity due to the fuzzy control and adaptive control somehow generally improves the robustness and load attenuation capabilities, as well as the dynamic performances of the PID controller.

Example 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 $M(s)$ is the same as former examples. The PID controller parameters which are tuned by (2) are as follows: $K_p = 3.4052$, $K_i = 1.7947$, $K_d = 3.6883$. The coefficients K_1, K_2 and K_3, which are the same as selected in former examples.

The step responses for several methods are reported in Fig.12. Obviously, the performance of MRFA-PID is better than the others. In order to verify the robustness, suppose the dead-time is increased by 20%, Fig.13 shows the step

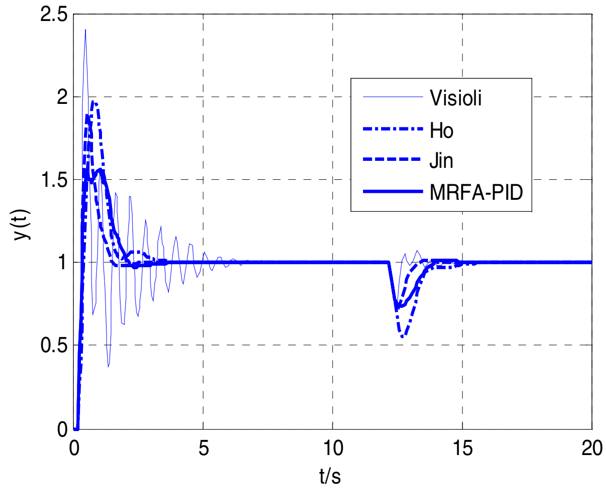

Fig.10. Step response for $G_3(s)$ at nominal case

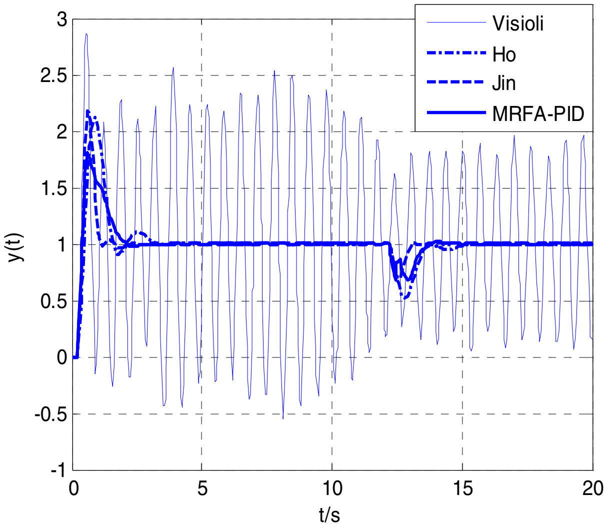

Fig.11. Step response for $G_3(s)$ at the parameter variation case

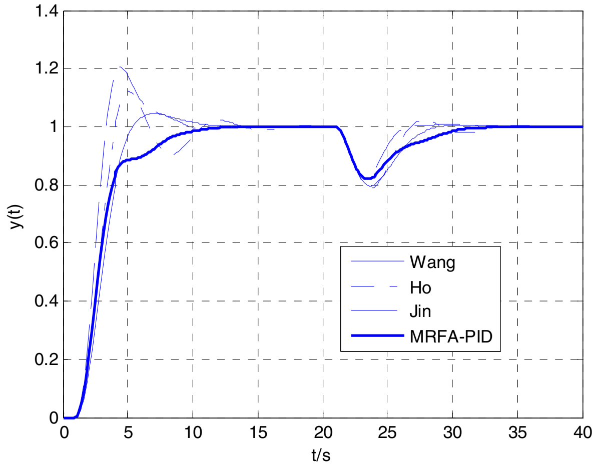

Fig.12. Step response for $G_4(s)$ at nominal case

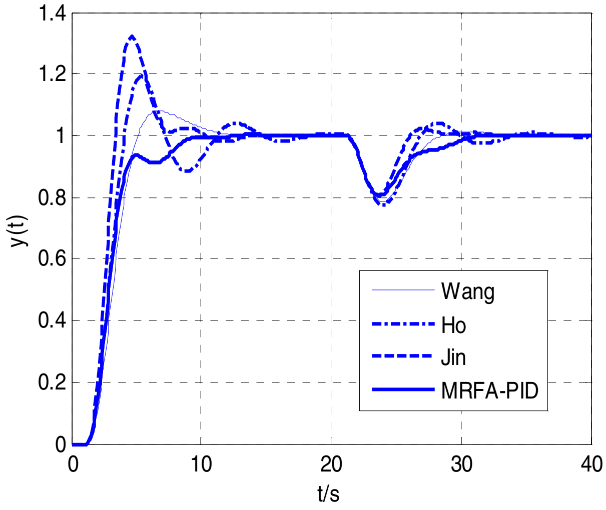

Fig.13. Step response for $G_4(s)$ at the parameter variation case

response at parameter variation case. The results show that the MRFA-PID has better robustness than the other methods.

In order to verify the load attenuation capabilities of the proposed controller, a load disturbance step has been applied to the plant at steady-state initial conditions. From the load-disturbance attenuation viewpoint, again, the MRFA-PID scheme is better than or equals to the others.

Some comparisons between the value of overshoot with MRFA-PID scheme and several other methods are shown in Table Ⅱ and Ⅲat nominal case and parameter variation case.

Other comparisons between the value of settle time with MRFA-PID scheme and several other methods are shown in Table Ⅳ and Ⅴ at nominal case and parameter variation case.

TABLE Ⅱ
VALUE OF OVERSHOOT (%) WITH MRFA-PID AND SEVERAL OTHER METHODS AT NOMINAL CASE

Prosess	Z-N	IMC	Jin	Poulin	Wang	Visioli	Ho	MRFA-PID
$G_1(s)$	40	16	20	—	—	—	—	0
$G_2(s)$	—	—	57	32	—	—	—	13
$G_3(s)$	—	—	85	—	—	140	90	55
$G_4(s)$	—	—	0	—	16	—	21	5

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

Prosess	Z-N	IMC	Jin	Poulin	Wang	Visioli	Ho	MRFA-PID
$G_1(s)$	64	30	39	—	—	—	—	0
$G_2(s)$	—	—	56	30	—	—	—	8
$G_3(s)$	—	—	80	—	—	136	90	60
$G_4(s)$	—	—	0	—	16	—	20	11

TABLE Ⅳ
VALUE OF SETTLE TIME (IN SECONDS) WITH MRFA-PID AND SEVERAL OTHER METHODS AT NOMINAL CASE

Prosess	Z-N	IMC	Jin	Poulin	Wang	Visioli	Ho	MRFA-PID
$G_1(s)$	3.0	4.0	3.8	—	—	—	—	3.7
$G_2(s)$	—	—	7.6	8.0	—	—	—	2.2
$G_3(s)$	—	—	1.8	—	—	6.2	3.0	2.0
$G_4(s)$	—	—	10.0	—	13.0	—	9.0	10.0

TABLE Ⅴ
VALUE OF SETTLE TIME (IN SECONDS) WITH SEVERAL METHODS AND

MRFA-PID AT PARAMETER VARIATION CASE

Prosess	Z-N	IMC	Jin	Poulin	Wang	Visioli	Ho	MRFA--PID
$G_1(s)$	4.5	4.0	3.0	—	—	—	—	3.0
$G_2(s)$	—	—	7.6	8.0	—	—	—	3.0
$G_3(s)$	—	—	1.0	—	—	---	2.6	1.7
$G_4(s)$	—	—	12.0	—	12.0	—	18.0	9.0

V. DISCUSSION

The use of the fuzzy control, model reference adaptive control, in conjunction with the adjust method of the proportional gain and the integral and derivative time constants, leads to a significant improvement in the step response dynamic performances and robustness, and preserves the good performances in the high regulation assured by the PID controller. Step response of the proposed controller gives lower overshoot, less settling time than the others. As an example, the values of in the case of the nominal parameters are reported in Tables Ⅱ and Ⅳ. It can be shown that the approach is also robust with respect to the plant parameter variations. As an example, the values in the case of the parameters variation are reported in Tables Ⅲ and Ⅴ. It can be noticed how the results are similar to the nominal case. It turns out that the application of the methodology is further simplified, since no great attention has to be paid in the initial tuning phase. Moreover, the reference model selecting can be easily to realize because they can be same for all the plants. Hence, the proposed approach seems to be particularly appropriate to be adopted in industrial environments, since it requires only a small computational effort, it is easy to apply, intuitive, and robust. Furthermore, the fuzzy control subsystem can be easily excluded from the overall control by making the coefficient K_3 to be zero. The proposed method need not identify the parameters of the controlled plant. Thus, it has a very good real-time performance, and is easy to be implemented on line.

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 shown to be very effective in the set-point following for a large number of processes. Step response gives lower overshoot and less settling time, the performance are insensitive to parameter variations of the system, whilst the high regulation and load disturbance attenuation performances obtained by the use of the PID controller are preserved or improved. The devised control structure seems to be particularly appropriate to be adopted in industrial settings, since it requires a small computational effort, it is easily tuned and it is compatible with a classical PID controller; that is, it consists of a module that can be added or excluded without modifying the parameters of the existing PID.

ACKNOWLEDGMENT

This work is supported by the Science and Technology Plan Instruction Project of Xiamen, China (3502Z2006008). The authors would like to thanks Dr. W. Lan from Xiamen University for his help to improve the presentation of this paper.

REFERENCES

[1] K. ÀstrÖm and T. Hägglund, PID Controllers: *Theory, Design and Tuning. New York*: ISA, 1995.

[2] X. Jin, W. Tan, Z.-J Li, J.-Z Liu. “Tuning of robust PID controllers for typical industrial processes”. *Control Theory & Applications*. vol. 22, no. 6, pp. 947-953, 2005. (In Chinese).

[3] Dr. F. H. Ali and Maher M. F. Algreer, “Fuzzy PID control for positioning plants with uncertain parameters variation,” *Information and Communication Technologies*, 2006. ICTTA '06. 2nd. Vol. 1, Date: 24-28, pp.1428-1433, April 2006.

[4] ÀstrÖm K J. Adaptive Control, 2nded. Beijing: Science Press, 2003.

[5] G. Chesi, A. Garulli, A. Tesi, and A. Vicino, “Homogeneous Lyapunov functions for systems with structured uncertainties,” *Automatica*, vol. 39, no. 6, pp.1027–1035, 2003.

[6] G. Chesi, A. Garulli, A. Tesi, and A. Vicino, “Polynomially parameter-dependent Lyapunov functions for robust stability of polytopic systems: an LMI approach,” *IEEE Trans. on Automatic Control*, vol. 50, no. 3, pp. 365–370, 2005.

[7] G. Chesi, A. Garulli, A. Tesi, and A. Vicino, “Robust stability of time-varying polytopic systems via parameter-dependent homogeneous Lyapunov functions,” *Automatica*, vol. 43, no. 2, pp. 309–316, 2007.

[8] İlyas Eker, Yunis Torun. “Fuzzy Logic Control to Be Conventional Method,” *Energy Conversion and Management*, Vol. 47, pp. 377-394. 2006.

[9] Khan, A.A. Rapal, N. “Fuzzy PID Controller: Design, Tuning and Comparison with Conventional PID Controller”, *2006 IEEE International Conference on Engineering of Intelligent Systems,* 22-23, pp.1- 6. April 2006.

[10] Stanislaw Skoczowski, Stefan Domek, Krzystof Pietrusewicz, and Bogdan Broel-Plater, “A Method for Improving the Robustness of PID Control”, *IEEE Transactions on Industrial Electronics*, vol. 52, NO. 6, pp. 1669-1676, December 2005.

[11] G. R. Liu, X. H. Yang, “Fuzzy Adaptive PID Controller”, *Control and Decision,* Vol. 10, No. 6, pp.558-562, 1995. (In Chinese).

[12] N. Wang. A fuzzy PID controller for multi-model plants. *Proceedings of the International Conference on Machine Learning and Cybernetics*, Beijing, pp.1401-1404, November 2002.

[13] P. J. Escamilla-Ambrosio and N. Mort. “A novel design and tuning procedure for PID type fuzzy logic controllers”. *2002 First International IEEE Symposium Intelligent Systems*, pp. 36-41, September 2002.

[14] M. Mizumoto. “Realization of PID controls by fuzzy control methods”. Fuzzy Sets and Systems, Vol. 70, pp. 171-182, 1995.

[15] M. J. E. Salami and Yusuf. L. Bulale. “Design and Implementation of fuzzy-based PID controller”, *IEEE ICIT’02, Bangkok, THAILAND*, pp.220-225, 2002.

[16] W. Zhu, X. H. Dong, Z. L. Zhang. “Modeling of fuzzy control in sheet deep drawing”. *Control Theory & Applications*. vol. 24, no. 1, pp. 122-126, 2007. (In Chinese).

[17] A Visioli. Fuzzy logic based set-point weight tuning of PID controllers[J]. *IEEE Transactions on Systems, Man, and cybernetic —Part A: Systems and Humans,* Vol. 29, No. 6, pp.587-592, 1999.

[18] Hayashi K, Otsubo A, Murakamj S, et al. Realization of nonlinear and linear PID controls using simplified indirect fuzzy inference method [J]. *Fuzzy Sets and Systems*, Vol. 105, No. 3, pp.409-414, 1999.

[19] Amin Haj Ali, P. Hao. Structural analysis of fuzzy controllers with nonlinear input fuzzy sets in relation to nonlinear PID control with variable gains. *Automatica*, Vol. 40, No. 9, pp.1551-1559, 2004.

[20] Y. Q. Peng, J. Luo and L. Q. Chen. Application of hybrid fuzzy PID in gelatin temperature control system based on PLC. *Journal of Xiamen University (Natural Science)*, Vol. 47, No.2, pp. 191-195, 2008. (In Chinese).