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Full Paper

An adaptive optimisation scheme for controlling air flow process with satisfactory transient performance

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Abstract: A non-identifier-based adaptive PI controller is designed using a gradient approach to improve the performance of a control system when device aging and environmental factors degrade the efficiency of the process. The design approach is based on the model reference adaptive control technique. The controller drives the difference (error) between the process response and desired model output to zero asymptotically at a rate constrained by the desired characteristics of the model. The tuning rules are designed and justified for a non-linear process with dominant dynamics of second order. The advantage of this method for tracking and regulation compared to adaptive MIT control was validated in real time by conducting experiments on a laboratory air flow control system using the dSPACE interface in the SIMULINK software. The experimental results show that the process with adaptive PI controller has better dynamic performance and robustness than that with traditional adaptive MIT controller.

Keywords: non-linear system, non-identifier-based adaptive control, model reference adaptive control (MRAC), adaptive MIT (AMIT) control, adaptive PI (API) control

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Introduction

Traditional non-adaptive controllers are generally “good enough” for most industrial process control applications. The ubiquitous proportional-integral derivative (PID) controller, or PID loop, is especially cheap and easy to implement. The simplicity of the PID controller also makes it fairly easy to understand and easy to diagnose [1]. A setpoint dependent or non-linear process can be particularly difficult to control with a fixed parameter controller since it reacts differently to the efforts of the controller depending on the current value of the setpoint. To improve the control performance, Li et al. [2] have applied the traditional PID, fuzzy PID, neural network PID, pole assignment method, optimal control and adaptive control methods to control non-linear systems. Under some specified conditions, these strategies prove to be effective. However, the above-mentioned control methods are within the domain of model-based control, built upon the system's mathematical model [3-5].

As most physical systems behave in a non-linear fashion, there exists a strong incentive to develop non-linear controller design methods. The usual approach to control non-linear systems is to linearise about an operating point the non-linear dynamics and apply proven linear control design approaches. The linearised model is then verified and validated by exhaustive computer simulations with the linear controller over a variety of initial conditions and disturbances. Such an approach is practical for only a small range of operating conditions. Hence, to control non-linear systems, adaptive controllers are designed. An adaptive controller adapts not only its output, but also its underlying control strategy, providing adaptation mechanisms (adaptive laws) that adjust a controller for a controlled system (plant) with parametric, structural or environmental uncertainties, to achieve a desired system performance [6-7]. It can tune its own parameters or otherwise modify its own control law so as to accommodate fundamental changes in the behaviour of the process. Thus the adaptive controller can significantly improve the system behaviour [6, 8].

Although adaptive controllers improve responses of the non-linear systems and systems with variable parameters, they are not yet used very often. The obvious reason is their complexity [9]. Considering the limitation of the above-mentioned control strategies, a model reference adaptive control (MRAC) has been developed and implemented to control a non-linear system. The idea of the MRAC is based on forcing the plant to follow the reference model, i.e. the adaptive controller has to decrease the error vector between the reference model and plant to zero. This method of MRAC has been implemented in the feedback loop to improve the performance of processes by many researchers [e.g. 10-11]. In all this work the gradient method of adaptation technique based on the minimisation of a chosen loss function (*J*) is applied. The MIT rule is the original approach to MRAC. The name MIT is derived from the fact that the rule was first developed at the instrumentation laboratory at Massachusetts Institute of Technology (MIT). Since MIT rule is used here for the adaptation of the controller parameters, it can be called as Adaptive MIT (AMIT) controller. In the present work, an auto-tuning of the proportional integral (PI) controller using MRAC concept is designed and implemented for a non-linear air flow process using the dSPACE Real Time Interface (RTI) card DS1104 (DS1104 – Digital Signal Processor used in dSPACE card). The DS1104 board of dSPACE performs the real-time control application, which is designed by SIMULINK and transferred to the board through Real-Time Workshop. The qualitative and quantitative improvement in the performance of the proposed controller to the traditional adaptive MIT (AMIT) controller is examined and the behaviour of this scheme is analysed.

However, a limitation of this gradient method of adaptation technique is that it is unsuitable for a system that exhibits fast dynamics because the period between the consecutive parameter updates has to be sufficiently long to ensure that all the system dynamics have enough time to contribute, directly or indirectly, to the cost function.

The rest of the paper is organised as the following: the non-linear air flow control system available in our lab is first described, followed by the section that deals with adaptive control algorithm. The real time implementation along with the results are presented in the last section before the concluding remarks.

Laboratory Air Flow Control System

The process considered in this paper is a simple laboratory air flow process. This process is non-linear but can show an acceptable range of linearisation. Air flow process can be modelled as a second-order process whose dynamics depends on operating conditions. The piping and instrumentation diagram (Figure 1) depicts the air flow process and its associated control system. The controlled variable (air flow rate) through the process line is measured by the electronic differential pressure flow transmitter (EDPFT). The sensor output is the feedback signal for closed-loop control via DS1104 dSPACE. The controller consists of the hardware of dSPACE DS1104 board and the software for the implementation of adaptive PI (API) control algorithm. The control algorithm runs in the DS1104 board and the real system data can be monitored by the control desk software. The connection scheme of air flow process is given in Figure 2a. Figure 2b provides the justification for treating the air flow process as a non-linear process.

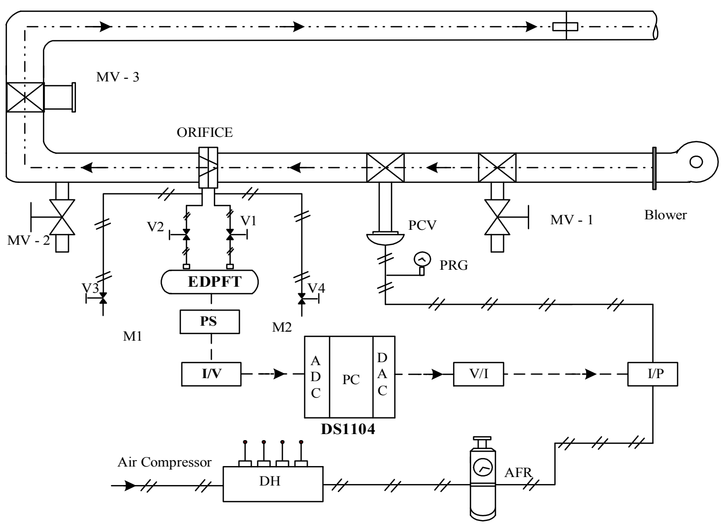

Figure 1. Piping and instrumentation diagram of laboratory air flow control system

(V1 to V4 - Manifold valves; MV-1 to MV-3 - Manual control valves; PS - Power Supply; M1 and M2 - Manometer connections; mA - Milliammeter; DH - De humidifier; I/P – Current-to-pressure converter; AFR - Air filter regulator; PCV - Pneumatic control valve; PRG - Pressure gauge ; G-2 - Galvanised pipe for cold air flow; EDPFT – Electronic differential pressure flow transmitter)

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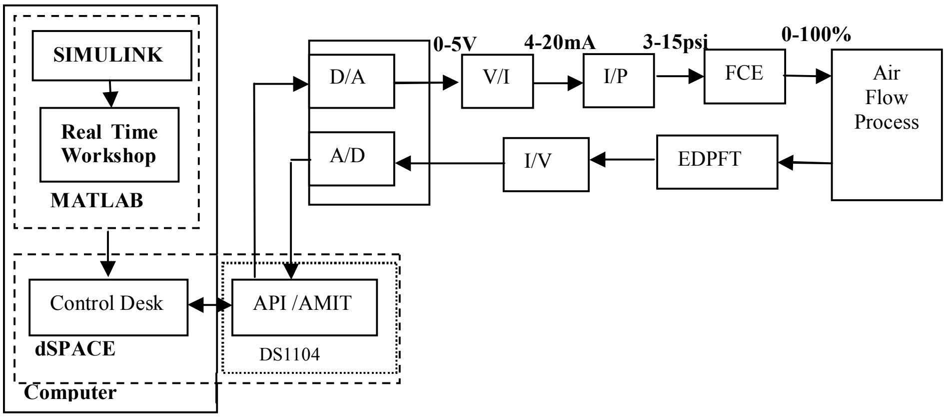

Figure 2(a). Connection scheme of air flow process
(D/A - Digital to Analog Convertor; A/D - Analog to Digital Convertor; I/V - Current to Voltage Convertor; V/I - Voltage to Current Convertor; I/P - Current to Pressure Convertor ; FCE - Final Control Element)

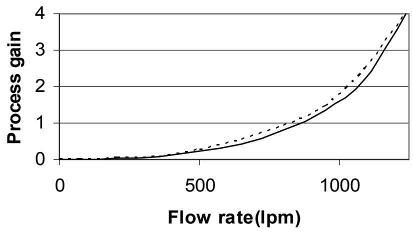

Figure 2(b). Characteristics of air flow process

--------- Increasing flow rate;
- - - - - - Decreasing flow rate;

Adaptive Control Algorithm

Most advanced control techniques for designing control systems are based on a good understanding of the process and its environment. If quantitative knowledge of the process is not available then the situation is usually called a “black-box” problem. In many cases the operator may have some knowledge of the process but is not sure whether the knowledge is accurate or not. This is usually called a “grey-box” problem. If quantitative knowledge of the process is available, a “white-box” model are to be dealt with.

Non-identifier-based adaptive control (*NIAC*)

A trade-off between the persistent excitation of signals for correct identification and steady system response for control performance exists. Non-identifier-based adaptive PI controller avoids this fundamental problem by not using any identification mechanism in the system [12]. The controller is defined to possess knowledge about the order and minimum relative degree of the process. The algorithm used in the controller updates its parameters based on the sole objective, viz. minimisation of the loss function.

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The structure of the control system with non-identifier-based adaptive PI controller is shown in Figure 3 [2]. This control system consists of a reference model, an adjustment mechanism and a controller. The reference model describes the desired input/output dynamics of the closed loop. The controller derives the control signal (U) so that the plant's closed-loop characteristics from the command signal U_C to the plant output (Y) is the same as the dynamics of the reference model. The convergence of the modelling error to zero for any given U_C is assured when Y exactly follows the output of the model (Y_M).

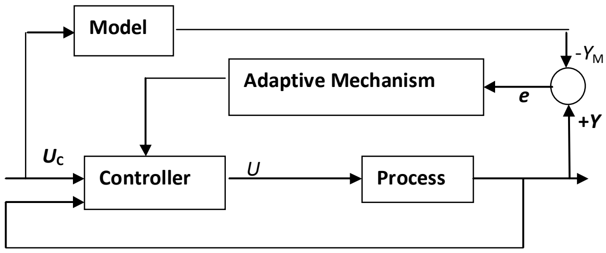

Figure 3. Block schematic diagram of the system with adaptive control (U_C - command signal; U - control signal; e - modelling error; Y - process output; Y_M - model output)

The modelling error e is given by equation (1):

$$e = Y - Y_M \tag{1}$$

The controller parameters are adjusted with the loss function $J(\theta)$:

$$J(\theta) = \tfrac{1}{2} e^2 \tag{2}$$

To minimise J, the parameters can be changed in the direction of negative gradient of J. The rate of change of controller parameters (θ) with respect to time is defined by equation (3) where the adaptation gain is defined by γ:

$$\frac{d\theta}{dt} = -\gamma \frac{dJ}{d\theta} = -\gamma e \frac{\partial e}{\partial \theta} \tag{3}$$

The following parameter adjustment mechanism, called MIT algorithm [6] and represented as in equation (4), is used to control the laboratory air flow control system:

$$\frac{d\theta}{dt} = -\gamma e \frac{\partial e}{\partial \theta} \tag{4}$$

Adaptive MIT (AMIT) algorithm

Although the adaptive control can actually deal with black-, grey- and white-box problems, it is more suitable for dealing with the grey-box one, since there is no need to apply a "no model" control method when a process is clear and it is not a good idea to attack a black-box problem without making the effort to understand the process. Based on a priori knowledge, the process is modelled as second order. The transfer function of the laboratory air flow process after linearisation can be represented by equation (5) as a function of Laplace transform (operator s, complex frequency variable) [13]:

$$\frac{Y}{U}=\frac{K}{s^2+a_1s+a_2} \tag{5}$$

where K, $a_1$and a_2 are positive and are the process parameters. The AMIT control law is given by

$$U=\theta_1 U_C-\theta_2 Y \tag{6}$$

The closed-loop transfer function related to the output and input with the AMIT controller in the loop is given by equation (7) [14]:

$$\frac{Y}{U_C}=\frac{K\theta_1}{s^2+a_1s+(a_2+K\theta_2)} \tag{7}$$

$$Y=\frac{K\theta_1}{s^2+a_1s+(a_2+K\theta_2)}U_C \tag{8}$$

where U_C is the command signal (reference input). The controller parameters (θ_1,θ_2) are updated by the adaptation mechanism such that the process output follows the model output (equation (9)):

$$\frac{Y_M}{U_C}=\frac{K_M}{s^2+A_1s+A_2} \tag{9}$$

where K_M, A_1 and A_2 are the reference model parameters. This model is introduced to match the structure of equation (8) and also has the same rise time and settling time as that of the reference model of adaptive PI controller [15]. The controller parameters are to be chosen as in equations (10) and (11) so that the input-output relations of the system and the model are the same. This is called perfect model following.

$$\theta_1=\frac{K_M}{K} \tag{10}$$

$$\theta_2=\frac{A_1s+A_2-a_1s-a_2}{K} \tag{11}$$

To apply the AMIT controller, the sensitivity derivatives are obtained by calculating the partial derivatives of modelling error with respect to the controller parameters θ_1 and θ_2. The process parameters K, a_1 and a_2 are not known. An approximation based on the observation : $s^2+a_1s+(a_2+K\theta_2)=s^2+A_1s+A_2$ is applied for perfect model following. Then,

$$\frac{\partial e}{\partial\theta_1}=\left(\frac{K}{s^2+A_1s+A_2}\right)U_c \tag{12}$$

$$\frac{\partial e}{\partial\theta_2}=-Y\left(\frac{K}{s^2+A_1s+A_2}\right) \tag{13}$$

Based on equations (12) and (13) the following equations are obtained for updating the controller parameters θ_1 and θ_2:

$$\theta_1=-\frac{\gamma'}{s}e\left(\frac{1}{s^2+A_1s+A_2}\right)U_C \tag{14}$$

$$\theta_2=\frac{\gamma'}{s}e\left(\frac{1}{s^2+A_1s+A_2}\right)Y \tag{15}$$

where $\gamma'=\gamma K$. By varying γ, the tracking speed and thus the controller parameter convergence rate are varied.

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Structure of AMIT reference model

The numerical values for the second-order reference model for equation (9) considered in this work are given below:

$$\frac{Y_M}{U_C} = \frac{K_M}{s^2 + A_1 s + A_2} = \frac{\omega_n^2}{s^2 + 2\delta\omega_n + \omega_n^2} = \frac{2.069}{s^2 + 1.41556s + 2.069}$$

The reference model for AMIT control is chosen with a damping ratio (δ) of 0.7 and natural frequency (ω_n) of 1.4 to match with the dynamics of the reference model of adaption PI control.

Adaptive PI (API) control

It is common that most of the industrial and mechatronic control systems are based on PI and PID controllers [1-2]. Even a slight modification in the design of PI controller can lead to large improvement for the industries. PI controllers are simple and easy to implement; hence, one based on MRAC using a gradient approach is designed and implemented in this work. The PI algorithm used in the controller is given by equation (16):

$$U = K_P(U_C - Y) + \frac{K_I}{s}(U_C - Y) \tag{16}$$

where K_P and K_I are the proportional and integral gains of the controller. Based on a priori knowledge the process considered for control is represented by equation (5). The closed-loop transfer function with PI controller is given by

$$\frac{Y}{U_C} = \frac{KK_P s + KK_I}{s^3 + a_1 s^2 + (a_2 + KK_P)s + KK_I} \tag{17}$$

The reference model to follow the dynamics, introduced to match the structure of equation (17), is given by equation (18):

$$\frac{Y_M}{U_C} = \frac{\alpha s + \beta}{s^3 + A_1 s^2 + A_2 s + A_3} \tag{18}$$

where α, β, A_1, A_2 and A_3 are the reference model parameters. For perfect model matching,

$$\begin{aligned} &s^3 + a_1 s^2 + (a_2 + KK_P)s + KK_I \\ &\qquad = s^3 + A_1 s^2 + A_2 s + A_3 \end{aligned} \tag{19}$$

Then, two approximate parameter-adaptation laws are derived by replacing θ in equation (4) with K_P and K_I. This results in equation (20) and (21) respectively:

$$K_P = -\frac{\gamma'}{s} e\left(\frac{s}{s^3 + A_1 s^2 + A_2 s + A_3}\right)(U_C - Y) \tag{20}$$

$$K_I = -\frac{\gamma'}{s} e\left(\frac{1}{s^3 + A_1 s^2 + A_2 s + A_3}\right)(U_C - Y) \tag{21}$$

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where the original adaptation gain γ is replaced by γ' $(=\gamma K)$. Thus, the controller parameters are manipulated by the adaptation mechanism to match the response of the process with the dynamics of the reference model. The performances of the designed AMIT and API controllers are observed by implementing them on a non-linear process in real time.

Structure of the API reference model

Based on equation (18), the reference model for the adaptive PI controller is given below. It has a damping factor of 0.7 and a natural frequency of 1. The remaining time constant is selected around 0.3 so that the dynamics is not much affected.

$$\frac{Y_M}{U_C} = \frac{\alpha s + \beta}{s^3 + A_1 s^2 + A_2 s + A_3} = \frac{10s + 10}{s^3 + 11.4s^2 + 15s + 10}$$

Real-Time Experimentation

Experimentation work was carried out to demonstrate the tracking capability of the proposed API and AMIT controllers using dSPACE. This system has the advantage of high computing power and the possibility to download models realised in MATLAB/SIMULINK to the real-time hardware in an automated way. In Figure 4(a) the air flow control system available in our laboratory is displayed. The hardware set-up to control the chosen process using dSPACE is presented in Figure 4(b).

Figure 4(a). Laboratory air flow control system

Figure 4(b). Experimental set-up for real-time implementation of adaptive controllers

A step change in the feed flow rate of 150 litres per minute (lpm) was introduced (from 1025 to 1175 lpm) at 20 seconds and the responses of the process with API and AMIT controllers are presented in Figures 5(a) and 5(b) respectively. The adaptation gain (γ) was set as 5 and 10 for AMIT controller and API controller. Figure 5(a) shows the tracking response of the process (Y) towards the model output (Y_M). The process output settled 9.63 seconds (γ=5) and 9.5 seconds (γ=10) after the application of servo disturbance. Figure 5(b) shows the tracking response of the process (Y) with AMIT controller for the same servo change. The process settled to the desired flow rate of 1175 lpm after 67 seconds of the applied input change with controller's adaptation gain of 10. With a decrease in the adaptation gain (γ=5), the process settled after 100 seconds for the same operating range. For the operating range of 1025 lpm the process settled with adaptation gain 10, but did not settle with adaptation gain 5. These responses reveal the need for proper selection of adaptation gain. The speed of response of the process with API controller was higher when compared to that of the process with AMIT controller.

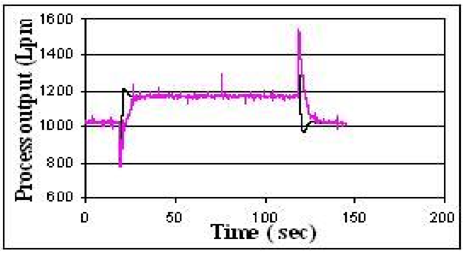

Figure 5(a). Process and model trajectories with API controller
------- Reference model output
------- Process output (API- γ = 5)
------- Process output (API- γ = 10)

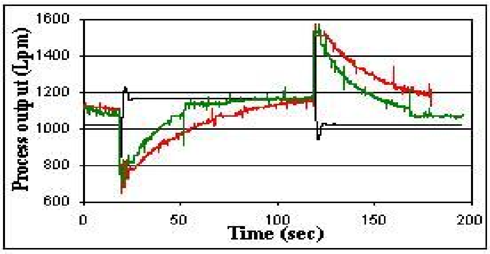

Figure 5(b). Process and model trajectories with AMIT controller
------- Reference model output
------- Process output (AMIT- γ =10)
------- Process output (AMIT- γ =5)

Various performance criteria of the system for the flow range of 1025 to 1175 lpm were observed and tabulated (Table 1). The speed of response of the process with API controller was 10 times more than that of the process with AMIT controller with the same adaptation gain (γ=5). The modelling error variation and the overshoot/undershoot of the process were 40% more with AMIT controller when the command signal changed from 1025 to 1175 lpm. In the decreasing range (1175-1025 lpm) there was no such significant change in the overshoot and undershoot.

Table 1. Performance criteria comparison for flow range of 1025-1175 lpm

Flow rate (1025 – 1175 lpm)	Adaptation gain	Increasing flow rate (1025-1175 lpm)		Decreasing flow rate (1175-1025 lpm)	
		AMIT	API	AMIT	API
T_S (sec)	5	100.00	9.6300	-	10.7000
	10	67.370	9.5000	53.3800	10.2000
os / us (lpm)	5	367.8200	235.4700	360.2500	337.5000
	10	313.0000	232.4700	358.2500	337.0000
Δe (lpm)	5	- 0.0700	-0.0300	0.0576	0.0300
	10	-0.0650	-0.0295	0.0557	0.0295
Δmv (volt)	5	0.0642	0.0505	0.0643	0.0527
	10	0.0624	0.0500	0.0625	0.0524
$\Delta\theta_1 / \Delta K_P$	5	0.0001	0.3652	0.0001	0.0001
	10	0.0001	0.3650	0.0001	0.0001
$\Delta\theta_2 / \Delta K_I$	5	0.0148	0.5308	0.0136	0.0136
	10	0.0149	0.7310	0.0138	0.0134

Note: Δmv - change in manipulated variable; T_s - settling time; os/us - overshoot/undershoot

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The servo and regulatory response of the process in the flow range of 575-725 lpm with AMIT controller (adaptation gain 5 and 10) is shown in Figures 6(a) and 6(b) respectively. The load disturbance was provided by manipulating the position of the manual valve MV-1 (Figure 1). The reference input signal was a square wave with amplitude of 150 lpm. When the air flow rate was 575 lpm, the manual valve MV-1 was opened at 90 seconds to bypass more air, thus disturbing the process flow rate (Figures 6(a)). Once the disturbance was rejected the MV-1 was brought back to its original position. At 725 lpm the regulatory disturbance was applied by opening the manual valve MV-1 at 190 seconds (Figures 6(a)).

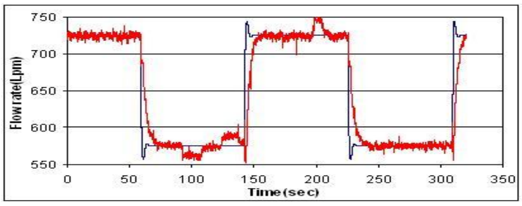

Figure 6(a). Servo and regulatory response of the process with AMIT controller (γ=5)
----- Response of the model
------- Response of the process

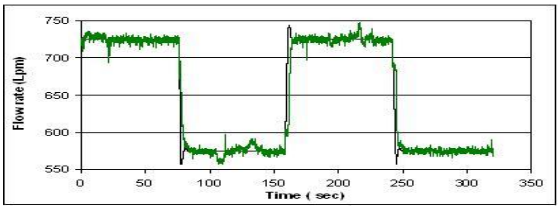

Figure 6(b). Servo and regulatory response of the process with AMIT controller (γ=10)
----- Response of the model
------- Response of the process

Initially the flow rate was at 725 lpm (Figure 6(a)). Then at 54 seconds the flow rate was changed to 575 lpm. The servo and regulatory response of the process presents improvement in tracking the set point and rejection of disturbance by increasing the adaptation gain from 5 to 10 (Figure (6(b)). For this decrease in flow rate the AMIT controller took action such that the adaptation of the controller parameter, θ1, decreased and θ2 increased (Figures 7(a) and 7(b)) to track the reference signal. To reject the regulatory disturbance, MRAC took action and the process was brought back to its nominal operating condition as shown in Figure 6(a) and 6(b).

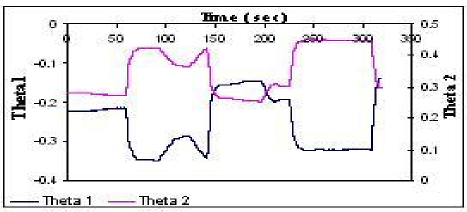

Figure 7(a). Adaptation of AMIT controller parameters (γ=5)

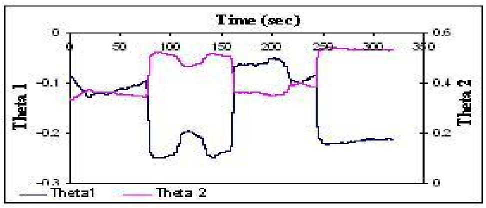

Figure 7(b). Adaptation of AMIT controller parameters (γ=10)

The response of the controlled system with API controller for adaptation gain of 5 and 10 is presented in Figures 8(a) and 8(b) respectively. The process was disturbed suddenly by rotating the manual valve MV-1 half turn counterclockwise at 105 seconds when the flow rate was 725 lpm and at 160 seconds when the flow range was 575 lpm (Figure 8(a)).

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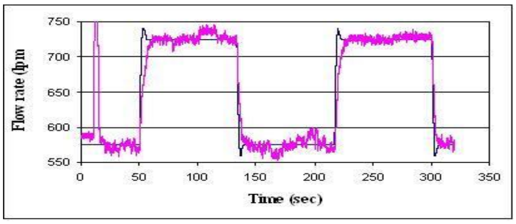

Figure 8(a). Servo and regulatory response of the process with API controller (γ=5)
----- Response of the model
------- Response of the process

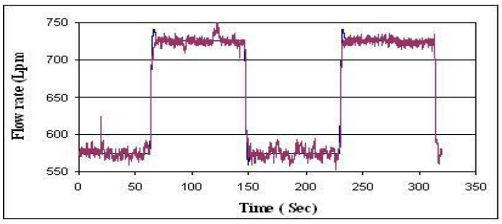

Figure 8(b). Servo and regulatory response of the process with API controller (γ=10)
----- Response of the model
------- Response of the process

The adaptation of the controller parameters for servo and regulatory changes are displayed in Figures 9(a) and 9(b). At the instant the servo changes or the regulatory disturbs the process, the adaptation of the controller parameters starts. After the flow rate settles to the desired value, the adaptation of the controller parameters vanishes and the controller operates with constant parameters. Tables 2 and 3 present the performance of the control systems with proposed AMIT and API controllers for the flow range of 575-725 lpm. Based on the quantitative data from Table 2 one can infer that the parameters such as settling time (T_S), change in manipulated variable (Δmv) and variation in controller parameters ($\Delta\theta_1 / \Delta K_P$, $\Delta\theta_2 / \Delta K_I$) are lower when adaptation gain is set to 10 compared to when it is set to 5 for servo and regulatory changes. Further, the controller parameter also converges at a faster rate with less manipulation in the controller output with γ=10.

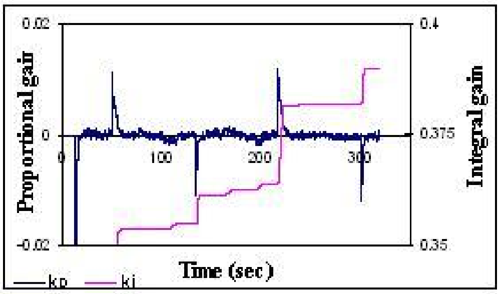

Figure 9(a). Adaptation of API controller parameters (γ=5)

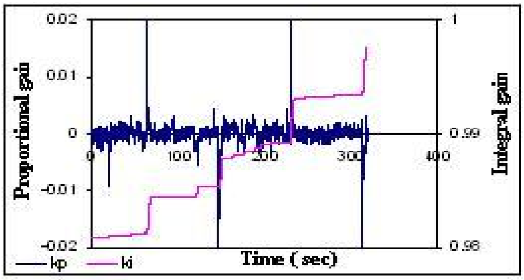

Figure 9(b). Adaptation of API controller parameters (γ=10)

Table 2. Performance comparison of the control systems

Flow rate	Parameter	Adaptation gain	Increasing flow rate (575-725 lpm)		Decreasing flow rate (575-725 lpm)	
			AMIT	API	AMIT	API
575-725 lpm (both servo and regulatory)	T_S (sec)	5	0.107	0.079	0.125	0.107
		10	0.079	0.072	0.075	0.071
	Δmv (volt)	5	0.057	0.0510	0.054	0.0380
		10	0.048	0.0060	0.052	0.0180
	$\Delta\theta_1/\Delta K_P$	5	0.184	0.0090	0.135	0.0090
		10	0.167	0.0030	0.146	0.0250
	$\Delta\theta_2 / \Delta K_I$	5	0.140	0.0120	0.150	0.0020
		10	0.136	0.0530	0.175	0.0030

Note: Ts - settling time; Δmv - change in manipulated variable

The performance comparison of the chosen process for load disturbance alone is presented in Table 3. For the load disturbance, the overshoot or undershoot (os/us) of the process is greater for AMIT controller and this is also the case for controller with adaptation gain 5. The speed of response of API controller is greater with minimal overshoot and undershoot. The load is applied by changing the position of the manual valve MV-1. It is applied and withdrawn for 575-lpm flow whereas for 725-lpm flow the MV-1 position is changed and is not brought back to its original position. The time integral performance criteria (integral square error (ISE), integral absolute error (IAE) and integral of time-weighted absolute error (ITAE) values) of the NIAC system under study are analysed in Table 4.

Table 3. Performance comparison of the systems with report to load disturbance

Flow rate	**Parameter**	**Adaptation gain**	**Increasing flow rate (575-725 lpm)**		**Decreasing flow rate (575-725 lpm)**	
			AMIT	**API**	**AMIT**	**API**
575-725 lpm (only regulatory)	T_S (sec)	5	179.600	120.7000	469.2000	447.600
		10	144.200	113.5000	370.8000	279.900
	os / us (lpm)	5	16.840	9.5800	13.12/13.28	12.91/11.4
		10	16.600	7.0200	9.41/9.96	7.71/5.64
	Δmv (volt)	5	0.026	0.0260	0.031	0.0260
		10	0.078	0.0060	0.018	0.0410
	$\Delta\theta_1 / \Delta K_P$	5	0.038	0.0009	0.062	0.0002
		10	0.049	0.0030	0.011/0.04	0.0040
	$\Delta\theta_2 / \Delta K_I$	5	0.040	0.0010	0.060	0.0020
		10	0.049	0.0010	0.040	0.0010

Note: T_s - settling time; os/us - overshoot/undershoot; Δmv - change in manipulated variable

Table 4. Comparison of time integral performance criteria of the systems

Flow rate	**Adaptation gain**	**ISE**		**IAE**		**ITAE**	
		AMIT	**API**	**AMIT**	**API**	**AMIT**	**API**
Both servo and regulatory (575-725 lpm)	5	$0.5368e^{-3}$	$0.1461e^{-3}$	$0.02317e^{-1}$	$0.1209e^{-2}$	9.1780	-0.4788
	10	$0.7455e^{-5}$	$0.1023e^{-5}$	$0.8634e^{-2}$	$0.1012e^{-2}$	-0.5421	-0.4007
Regulatory alone (575 lpm)	5	613.4000	18.3300	42.8100	24.7700	8990.0000	-3512.0000
	10	2048.0000	93.8900	45.2500	9.6900	9729.0000	-1541.0000
Regulatory alone (725 lpm)	5	40050.0000	25190.0000	200.1000	158.7000	352200.0000	25620.0000
	10	5774.0000	5052.0000	75.9900	71.0800	164200.0000	9498.00000

The practical results presented reveal the dynamic character of the applied strategy. The comparative study indicates that the performance of the process with API controller is better than that with AMIT controller. The performance analysis based on the above-mentioned criteria for regulatory response alone also reveals that the API controller outperforms the AMIT controller.

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Conclusions

The automatic tuning of PI controller has been investigated using MRAC concept and AMIT rule. Simple adaptation laws for the controller parameters are presented for a second-order process with third-order reference model. Furthermore, when the technique is applied to a non-linear laboratory air flow process, the overall system performance with adaptive PI is observed to have better tracking and disturbance rejection than that of the system with AMIT controller. From the plots, it is clear that the transient performance in terms of tracking error and control signal has been significantly improved by the API controller. Its adaptation gain variations are negligible when compared to the AMIT controller. Due to this, the adaptation of the controller parameters vanishes at a faster rate for API controller. The resulting performance could be improved by a better choice of the adaptation gain. Thus, the API controller supports the process to track the desired model response at a faster rate with less control effort.

A major setback in the AMIT rule is the speed of adaptation, and second, the AMIT rule does not guarantee the stability of the nominal system. The Lyapunov approach can be used to provide guaranteed nominal stability.

A further limitation of the approach is the assumption of the structure for the nominal system. In this paper a second-order model is used and may be simple for many applications. A more flexible nominal model could be used at the expense of more complicated adaptation laws.

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References

1. K. J. Astrom and T. Hagglund, "PID Controllers: Theory, Design and Ttuning", 2nd Edn., Instrument Society of America, Research Triangle Park, North Carolina, **1995**.
2. G. Li, J. Ma and G. Zhao, "Simulation comparisons among PID control, adaptive control and MFC on ship anti-rolling tank test platform", Proceedings of IEEE International Conference on Mechatronics and Automation, **2007**, Harbin, China, pp 3948-3953.
3. K. Sukvichai , "The application of nonlinear model reference PID controller for a planar robot arm", Proceedings of ECTI-CON, **2008**, Krabi, Thailand, pp. 637-640.
4. X. Guo-kail, "Research on discrete model reference adaptive control system of electric vehicle", Proceedings of SICE- ICASE International Joint Conference, **2006**, Busan, South Korea, pp. 2430–2433.
5. R. Marino and P. Tomei, "Adaptive control of linear time-varying system", *Automatica*, **2003**, *39*, 651-659.
6. K. J. Astrom and B. Wittenmark, "Adaptive Control", 2nd Edn., Pearson Education, Singapore, **1995**.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 221-234

7. V. V. Chalam, “Adaptive Control Systems – Techniques and Applications”, Marcel Dekker, New York, **1987**.
8. G. Tao, “Adaptive Control Design and Analysis”, John Wiley and Sons, New York, **2003**.
9. R. Marino and P. Tomei, “Robust adaptive regulation of linear time-varying systems”, *IEEE Trans. Autom. Control*, **2000**, *45*, 1301-1311.
10. C. Quek, “Direct method for model reference adaptive PI controller using the gradient approach”, Proceedings of IEEE TENCON ‘93, **1993**, Beijing, China, pp.447-450.
11. B. Wang, “Model reference adaptive tension control of web packaging material”, Proceedings of International Conference on Intelligent Computation Technology and Automation, **2008**, Hunan, China, pp.395-398.
12. J. Zhang, “Non-identifier based adaptive control scheme with guaranteed stability”, Proceedings of the 2006 American Control Conference, **2006,** Minneapolis, Minnesota, USA.
13. R. S. Burns, “Advanced Control Engineering”, Butterworth-Heinemann, New Delhi, **2001**, pp. 40-41.
14. K. Ogata, “Modern Control Engineering”, Prentice Hall of India, New Delhi, **2003**.
15. C. Quek, “Direct method for model reference adaptive PI controller using the gradient approach”, Proceedings of IEEE TENCON ‘93, **1993**, Beijing, China, pp. 447-450.