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Control of a Thermal Airflow Process with Time-Delay - Part II: Adaptive Self-Tuning Control

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***Abstract* — This article was motivated from a practical work on modeling and control of a time-delayed thermal airflow process using adaptive techniques. The work was divided into two parts: (I) the modeling of the process using system identification methods, with main concerns to the numerical robustness of the identification, and (II) the digital control of the process using adaptive self-tuning control, with main concerns to the adaptation of the controller to changes in the process dynamics. This article concerns the second part of the work. An adaptive self-tuning controller was implemented to improve the performance of the thermal airflow process. At each sampling interval, the process model is updated using an on-line identification strategy developed in the first part of the work. Based on the identification, the controller is self-tuned to compensate for eventual changes in the process parameters. Intentional disturbances were made in the process dynamics in order to evaluate the adaptation performance of the control system.**

***Index Terms* — adaptive control, pole placement, self-tuning control, system identification.**

I. Introduction

Temperature is one of the most common variables in industrial processes and manufacturing systems. Most temperature control applications are *regulating control problems*, in which the goal is to stabilize the temperature at a fixed reference value (set-point). Other applications are *tracking control problem*, in which the goal is to follow a varying reference. A particular aspect of some thermal process is that they may be significantly affected by external conditions such as variations in the environment temperature, as well as by internal changes such as sensor relocation. In such cases, although a fixed-parameter controller might also improve the process performance, an *adaptive* controller with the ability to self-tune its parameters according to changes in the process dynamics should provide a more improved performance [4][8][10].

The term *adaptive system* means a system with ability to perform real-time adaptation in response to changes on its dynamics, normally in the form of *parametric variations*. By this way, an adaptive controller has the role to control a process not only to provide suitable response performance, but also to allow the entire system to adapt itself to eventual changes on its dynamics. Adaptation mechanisms are best implemented by means of computing algorithms, and therefore adaptive controllers are inherently discrete-time controllers. One way to classify the generic types of controller adaptation strategies is [19]:

1. **Parametric Adaptation**, by which the *parameters* of the controller (e.g.: the values of its transfer function coefficients) are modified in real-time, in response to changes in the process or disturbance dynamics. In other words, the controller is continually tuned, with no change on its structure. Controllers with this adaptation ability are called **self-tuning controllers** or **self-tuning regulators**.
2. **Structural Adaptation**, by which the *structure* of the controller (e.g.: its transfer function), as well as its parameters, is modified in real-time, in response to changes in the process or disturbance dynamics. Controllers with this adaptation ability can be regarded as **fully adaptive controllers**.

From the above definitions, self-tuning control is indeed a specific class of adaptive control, as illustrated in Fig. 1. It has been the dominant form of adaptive control, and the literature usually refers to self-tuning controllers as adaptive controllers with little formal distinction between them. In this work, the term "adaptive" is used with the meaning of "self-tuning".

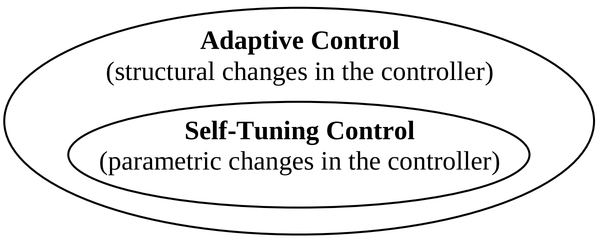

Fig. 1. Relationship between adaptive control and self-tuning control.

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Historically, the first self-tuning controllers were formulated when no digital computers were yet available. They were hardly and costly implemented with analog technologies. From the 60's to 70's, advances in the digital technology allowed a decisive impulse to the development and implementation of discrete-time self-tuning controllers [8]. Today, adaptive controllers are considered inherently digital controllers.

II. The System To Be Controlled

The system used for the application of adaptive control in this work is the thermal airflow system "Process Trainer PT-326" [1], by Feedback Instruments Limited, shown in Fig. 2. In this system, a rotating impeller generates an airflow through an open-end duct. The impeller rotation is manually adjusted to generate a fixed air flowrate. At the inlet of the duct, immediately after the impeller, there is a heating wire grid of Ni-Cr alloy, powered by a variable current source excited by a control signal, to heat the airflow generated by the impeller. The duct has three (left, central, and right) ports for insertion of a sensor (thermistor) probe into the duct, to measure the airflow temperature, which is the process variable to be controlled. A particular aspect of this thermal process is the existence of a small time-delay in the temperature response due to the displacement between the heating grid (actuator) at the inlet of the duct and the port where the thermistor probe (sensor) is inserted into the duct. Those time-delays were [19]: $\boldsymbol{\tau_1}$ **= 0.214 sec** (left port, at 28 mm), $\boldsymbol{\tau_2}$ **= 0.257 sec** (central port, at 140 mm), and $\boldsymbol{\tau_3}$ **= 0.341 sec** (right port, at 274 mm). Another particular aspect is that the process dynamics may change with variations in the external ambient air impelled into the duct. Even though those changes are small, they do exist.

To put the system into operation, the temperature probe is inserted into one of the duct ports, and the impeller rotation is adjusted to a fixed level. Fig. 3 shows the open loop step response of the system, which has a great steady state error. For a set-point of 40 °C (6.50 volts), the steady state temperature settled around 31 °C (3.68 volts). Eliminating the steady state error was the primary motivation for the design of a digital controller.

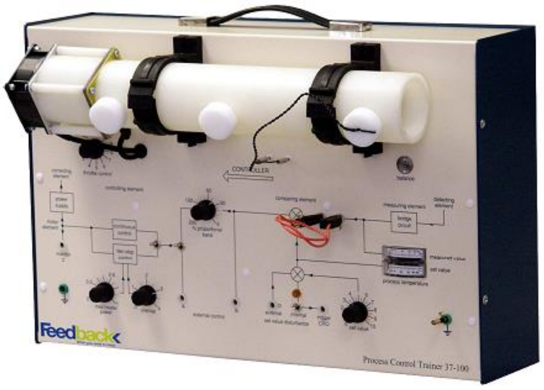

Fig. 2. Front view of the thermal airflow system PT-326.

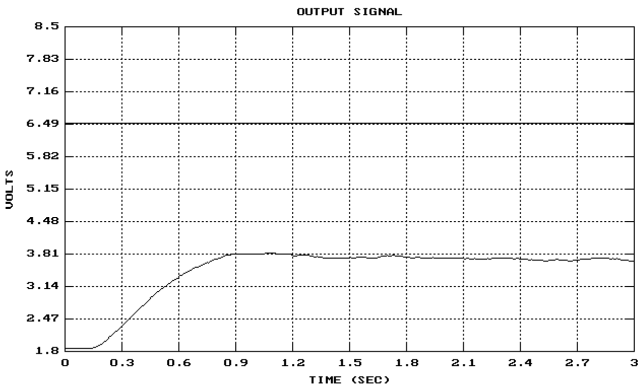

Fig. 3. Open loop step response of PT-326.

The thermal process was represented by an **ARMAX** (**A**uto-**R**egressive **M**oving **A**verage with E**x**ogenous Input) model given by [17]:

$$
\begin{aligned}
Y(z) &= z^{-1}\frac{B(z^{-1})}{A(z^{-1})}U(z)+\frac{C(z^{-1})}{A(z^{-1})}\Xi(z)\\
A(z^{-1}) &= 1+a_1z^{-1}\\
B(z^{-1}) &= b_0+b_1z^{-1}+b_2z^{-2}\\
C(z^{-1}) &= 1+c_1z^{-1}+c_2z^{-2}
\end{aligned}
\tag{1}
$$

where $Y(z)$ is the process output (temperature); $U(z)$ is the process input (control signal to the heating grid); and $\Xi(z)$ is a process noise. The parameters of model (1) were determined by system identification using the Recursive Extended Least Squares (RELS) method [18][4].

Since the recursive identification provides on-line updates of the process model, a self-tuning controller was designed using the **pole-placement** method. This method was chosen due to its flexibility to implement various controller types.

III. Self-Tuning Pole-Placement Control

A. Generic Self-Tuning Pole-Placement Controller

Suppose a process to be controlled is represented by an ARMAX model:

$$A(z^{-1})Y(z)=z^{-k}B(z^{-1})U(z)+C(z^{-1})\Xi(z) \tag{2}$$

where k is the discrete time-delay ($k \geq 1$). A generic controller structure for pole-placement control is shown in Fig. 4 [3], where $M(z^{-1})$, $P(z^{-1})$, and $S(z^{-1})$ are polynomials in z^{-1}, with $M(z^{-1})$ monic.

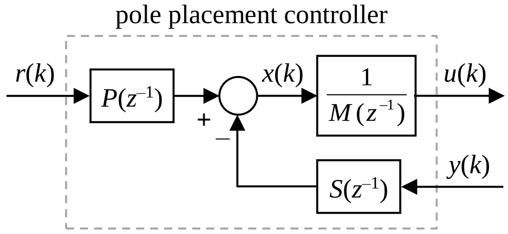

Fig. 4. Generic controller structure for pole-placement control.

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From the above structure, the control signal is:

$$U(z)=\frac{P(z^{-1})R(z)-S(z^{-1})Y(z)}{M(z^{-1})} \tag{3}$$

The closed loop response $Y(z)$ of the process is obtained by replacing (3) in (2):

$$\begin{aligned}Y(z)=&\left(\frac{z^{-k}B(z^{-1})P(z^{-1})}{A(z^{-1})M(z^{-1})+z^{-k}B(z^{-1})S(z^{-1})}\right)R(z)+\\&+\left(\frac{C(z^{-1})M(z^{-1})}{A(z^{-1})M(z^{-1})+z^{-k}B(z^{-1})S(z^{-1})}\right)\Xi(z)\end{aligned} \tag{4}$$

From (4), the poles of the closed loop system are the roots of the following **Diophantine Equation**:

$$A(z^{-1})M(z^{-1})+z^{-k}B(z^{-1})S(z^{-1})=T(z^{-1})=0 \tag{5}$$

In a pole-placement design, the polynomial $T(z^{-1})$ is chosen as the one whose roots are all the required poles (dominants and non-dominants) for the closed loop system, according to the performance requirements. Since $A(z^{-1})$ and $B(z^{-1})$ are obtained from system identification, $M(z^{-1})$ and $S(z^{-1})$ are determined by matching the coefficients with same power in z^{-1} in (5).

B. PID Self-Tuning Pole-Placement Controller

The pole-placement method allows the implementation of several controller structures. The structure chosen to control the thermal airflow process PT-326 was the Proportional-Integral-Derivative (PID) controller, due to the ability of its integral term to eliminate the steady state error of the step response of the process. The PID controller was designed according to the approach proposed in [7], in order to allow processes with higher order polynomials $B(z^{-1})$, which occurs when the discrete delay exponent k is greater than 1, but it is set to 1 and the polynomial $B(z^{-1})$ is set to higher orders. This approach is based on three principles:

1. The polynomial $M(z^{-1})$ is factorized as the product of two monic polynomials, $Q(z^{-1})$ and $H(z^{-1})$.

2. The structure of the PID controller is given by:

$$\frac{U(z)}{E(z)}=\frac{K_0+K_1z^{-1}+K_2z^{-2}}{(1-z^{-1})Q(z^{-1})} \tag{6}$$

   where the monic polynomial $Q(z^{-1})$ was included in the denominator of the controller transfer function. $U(z)$ is the control signal, and $E(z)$ is the error between the reference signal and the process output $Y(z)$, that is, $E(z) = R(z) – Y(z)$.

3. Equation (6) is associated with the general control law by:

$$\begin{cases}H(z^{-1})=1-z^{-1}\\M(z^{-1})=Q(z^{-1})H(z^{-1})\\P(z^{-1})=S(z^{-1})=K_0+K_1z^{-1}+K_2z^{-2}\end{cases} \tag{7}$$

From the above conditions, the characteristic equation (5) for the closed loop system becomes:

$$A(z^{-1})Q(z^{-1})H(z^{-1})+z^{-k}B(z^{-1})S(z^{-1})=T(z^{-1})=0 \tag{8}$$

The order of $T(z^{-1})$ is:

$$n_t=\max\{\,n_a+n_q+1\ ;\ n_b+k+2\,\} \tag{9}$$

The number of parameters to be determined in (8) is n_q+3: the three controller gains (K_1, K_2, and K_3), and the coefficients of the monic polynomial $Q(z^{-1})$. By matching the terms with same power in z^{-1} in (8), the number of linear independent equations that are obtained cannot exceed the number of parameters to be determined, and therefore:

$$n_t=\max\{\,n_a+n_q+1\ ;\ n_b+k+2\,\}\le n_q+3 \tag{10}$$

so that:

$$n_a\le 2\ \ ;\ \ n_b+k\le n_q+1 \tag{11}$$

Notice that the second inequality in (11) means that the inclusion of $Q(z^{-1})$ in the controller transfer function (6) allows the control of processes with $n_b > 0$, specially for processes with long time-delay.

Recall from the process model (1) that $k = 2$. Without lack of generality, we can set $k = 1$ and increase the order of polynomial $B(z^{-1})$ by k–1, and suppose that the k–1 terms b_j with higher order are identically null.

The controller design consists in determining the parameters $\{K_1, K_2, K_3, q_1, q_2, \ldots, q_{nq}\}$ by solving the set of linear equations resulting from the closed loop characteristic equation (8), where:

$$\begin{cases}T(z^{-1})=1+t_1z^{-1}+t_2z^{-2}+\ldots+t_{n_t}z^{-n_t}\\A(z^{-1})=1+a_1z^{-1}+a_2z^{-2}\\B(z^{-1})=b_0+b_1z^{-1}+b_2z^{-2}+\ldots+t_{n_b}z^{-n_b}\\Q(z^{-1})=1+q_1z^{-1}+q_2z^{-2}+\ldots+q_{n_q}z^{-n_q}\\H(z^{-1})=1-z^{-1}\\S(z^{-1})=K_0+K_1z^{-1}+K_2z^{-2}\end{cases} \tag{12}$$

IV. Controller Design for The Thermal Process

The discrete model of the thermal process is given by (1). From (6) and (10), the order of the polynomial $Q(z^{-1})$ is determined from two inequalities:

$$\begin{array}{ll}n_a+n_q+1\le n_q+3 & n_b+k+2\le n_q+3\\4\le n_q+3 & 5\le n_q+3\\n_q\ge 1 & n_q\ge 2\end{array} \tag{13}$$

To comply with the inequalities in (9), the order of $Q(z^{-1})$ must be $n_q \geq 2$. For the sake of simplicity, it was chosen as $n_q = 2$, so that:

$$Q(z^{-1}) = 1 + q_1 z^{-1} + q_2 z^{-2} \tag{14}$$

Hence, the order of the characteristic polynomial $T(z^{-1})$, given by (9) is:

$$\begin{aligned} n_t &= \max\{1+2+1 \; ; \; 2+1+2\} = \max\{4 \; ; \; 5\} \\ n_t &= 5 \end{aligned} \tag{15}$$

so that:

$$T(z^{-1}) = 1 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3} + t_4 z^{-4} + t_5 z^{-5} \tag{16}$$

Next, from (8), (12) and (16), the following identity is obtained:

$$\begin{aligned} &1 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3} + t_4 z^{-4} + t_5 z^{-5} = \\ &= (1 + a_1 z^{-1})(1 + q_1 z^{-1} + q_2 z^{-2})(1 - z^{-1}) + \\ &+ z^{-1}(b_0 + b_1 z^{-1} + b_2 z^{-2})(K_0 + K_1 z^{-1} + K_2 z^{-2}) \end{aligned} \tag{17}$$

Matching the terms in (17) with same power in z^{-1}, the following set of equations is obtained:

$$\begin{cases} t_1 = q_1 + (a_1 - 1) + b_0 K_0 \\ t_2 = q_2 + q_1(a_1 - 1) + (-a_1) + b_0 K_1 + b_1 K_0 \\ t_3 = q_2(a_1 - 1) + q_1(-a_1) + b_o K_2 + b_1 K_1 + b_2 K_0 \\ t_4 = q_2(-a_1) + b_1 K_2 + b_2 K_1 \\ t_5 = b_2 K_2 \end{cases} \tag{18}$$

which can be written as:

$$\begin{cases} t_1 - (a_1 - 1) = q_1 + b_0 K_0 \\ t_2 - (-a_1) = (a_1 - 1) q_1 + q_2 + b_1 K_0 + b_0 K_1 \\ t_3 = (-a_1) q_1 + (a_1 - 1) q_2 + b_2 K_0 + b_1 K_1 + b_0 K_2 \\ t_4 = (-a_1) q_2 + b_2 K_1 + b_1 K_2 \\ t_5 = b_2 K_2 \end{cases} \tag{19}$$

which corresponds to the matrix equation:

$$\begin{bmatrix} 1 & 0 & b_0 & 0 & 0 \\ a_1 - 1 & 1 & b_1 & b_0 & 0 \\ -a_1 & a_1 - 1 & b_2 & b_1 & b_0 \\ 0 & -a_1 & 0 & b_2 & b_1 \\ 0 & 0 & 0 & 0 & b_2 \end{bmatrix} \times \begin{bmatrix} q_1 \\ q_2 \\ K_0 \\ K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} t_1 - (a_1 - 1) \\ t_2 - (-a_1) \\ t_3 \\ t_4 \\ t_5 \end{bmatrix} \tag{20}$$

$$\mathbf{M} \times \mathbf{K} = \mathbf{T}$$

so that the controller parameters are determined from:

$$\mathbf{K} = \begin{bmatrix} q_1 \\ q_2 \\ K_0 \\ K_1 \\ K_2 \end{bmatrix} = \mathbf{M}^{-1} \times \mathbf{T} \tag{21}$$

Therefore, provided that the process parameters in the matrix **M** are estimated on-line by system identification, equation (21) implements an adaptive self-tuning controller. The system identification of the thermal process PT-326 was performed using the Recursive Least Squares method with UD Factorization and forgetting factor, as described in [18].

The performance specifications for the closed loop system were: a settling time $t_s = 1$ **sec** and a maximum overshoot $M_p = 1\%$. The necessary damping factor ξ and natural frequency ω_n to meet these requirements are: $\xi = 0.826$ and $\omega_n = 4.843$ **rad/s**. Therefore, the required continuous poles for the closed loop system are given by [11]:

$$s_i = -\xi\omega_n \pm j\omega_n\sqrt{1-\xi^2} = -4 \pm j2.73 \tag{22}$$

For a sampling period T = 0.2 sec, the corresponding discrete poles are [11]:

$$z_i = e^{s_i T} = e^{(4 \pm j2.73)0.2} = 0.384 \pm j0.233 \tag{23}$$

The discrete poles z_i must be the roots of the characteristic closed loop polynomial $T(z^{-1})$, that is:

$$T(z^{-1}) = 1 - 0.768 z^{-1} + 0.201745 z^{-2} + 0 z^{-3} + 0 z^{-4} + 0 z^{-5} \tag{24}$$

The block diagram of the adaptive control system is shown in Fig. 5. The control system was implemented with the following steps:

1. At the current time k, get the reference input $r(k)$ and acquire the process output $y(k)$ from the A/D converter.
2. Using the previous estimate of the process parameters and controller parameters, compute the control signal $u(k)$ from equation (6), add a small PRBS signal to $u(k)$, and apply it to the process using the D/A converter.
3. Perform the system identification to update the process parameters, and compute matrix **M** in (20).
4. Update the controller parameters using (21), therefore making it adaptive.
5. Wait for the next sampling time and return to step 1.

In step 2 above, a small **PRBS** (**P**seudo-**R**andom **B**inary **S**ignal) was added to the ordinary control signal $u(k)$ to assure that the process is *persistently excited*, a necessary condition for the system identification [8].

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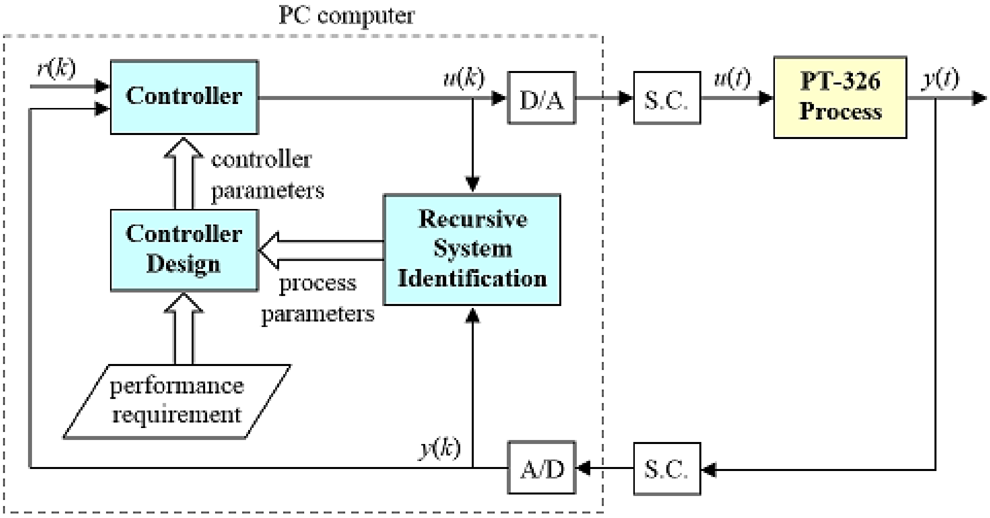

Fig. 5. Block diagram of the adaptive self-tuning control system.

Notes:

1. The system identification and adaptive control algorithms were implemented with the C++ language.
2. "S.C." is Signal Conditioning, "A/D" is Analog-to-Digital conversion, and "D/A" is Digital-to-Analog conversion.
3. The A/D and D/A conversions were performed with an ACL-812PG AD/DA data acquisition board installed in the PC computer.
4. The signal conditioning for the process output $y(k)$ and the control signal $u(k)$ were performed by proper active analog circuits.
5. The performance requirement is simply the closed loop characteristic equation, which defines the required closed loop poles.

The system identification and adaptive control were implemented in a PC computer using the C++ programming language. A data acquisition board [1] installed in the computer provided the necessary A/D and D/A interfaces with the process. To solve equation (21), the inverse of matrix **M** was computed using the Gauss Elimination method [12].

V. Closed Loop System Performance

The performance of the thermal process with the adaptive control was evaluated from its closed loop step response. Two performance tests were done: (1) the application of a single step input $r(k)$, to evaluate the close loop response with regards to the open loop response; and (2) the same previous test plus a change in the process dynamics, to evaluate the ability of the adaptive controller to stabilize the process output as well as to compensate for the change in the process dynamics.

A. *Performance with no disturbances on the process*

With the PT-326 system in closed loop, its temperature probe was placed at the central port of its duct. A reference temperature of 40 ºC (6.50 volts) was required for the airflow, so that a step input $\boldsymbol{r(k)}$ **= 15 ºC** (4.70 volts) was applied to the process input to move it from the ambient temperature of 25 ºC (1.80 volts) to 40 ºC. The measured temperature response to this step input is shown in Fig. 6. The response had a settling time around 2 sec (10 sample times) and a maximum overshoot of around 2%. Notice that since the adaptive control system starts the identification at time k=0, the settling time and the overshoot of the step response resulted slightly different from the performance specifications related to the poles in (22) and (23). Comparing with the open loop response in Fig. 3, the closed loop response is still fast, has low overshoot, and does not have steady state error, indicating the effectiveness of the controller to eliminate the steady state error, shown in Fig. 7. The control signal is shown in Fig. 8. The open loop step response shown in Fig. 3 has a rise time of around 0.8 sec (4 sample times), which is virtually the same observed in the closed loop step response shown in Fig. 6.

The process output temperature has a little noise due to the inherent turbulence of the airflow inside the duct, and to the small PRBS component added to the control signal.

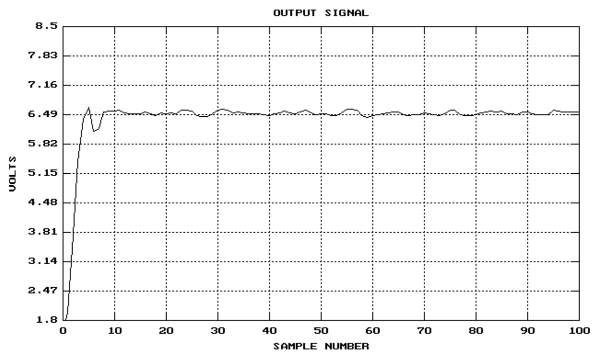

Fig. 6. Closed loop step response.

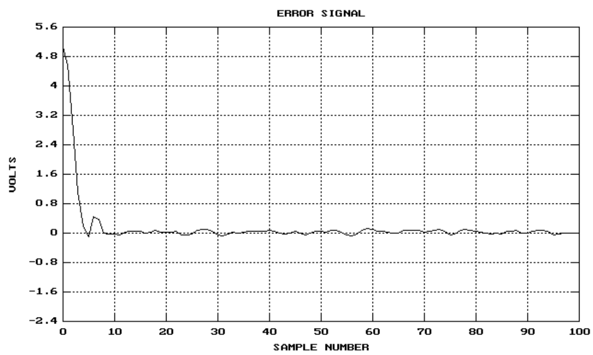

Fig. 7. Error of the closed loop step response.

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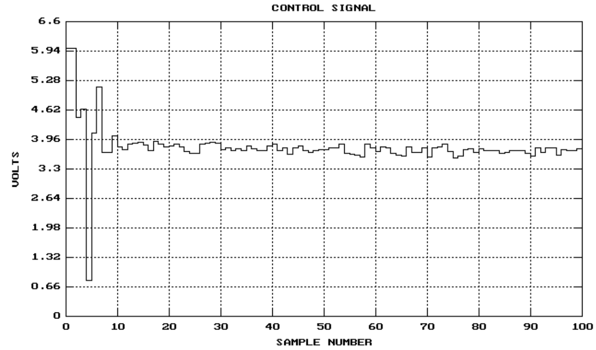

Fig. 8. Control signal from the adaptive self-tuning controller.

Fig. 9 to Fig. 12 show the estimates of the process parameters (the coefficients of polynomials $A(z^{-1})$ and $B(z^{-1})$ in (1)) resulted from the recursive identification performed along with the adaptive control. The prediction error is shown in Fig. 13. In the beginning of the test, the prediction error is high due to the inaccuracies in the initial values of the model parameters. As the parameter estimates converge to their “true” values, the prediction error tends to zero. These results clearly indicate a consistent convergence of the system identification.

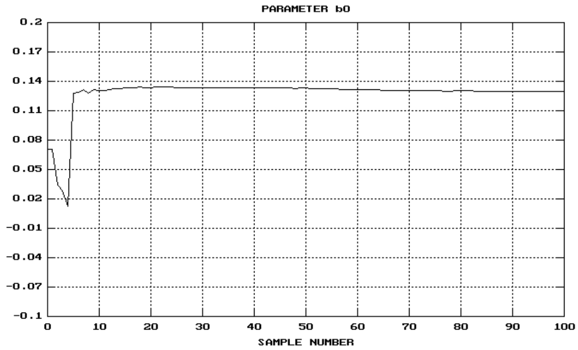

Fig. 9. Estimate of process parameter b_0.

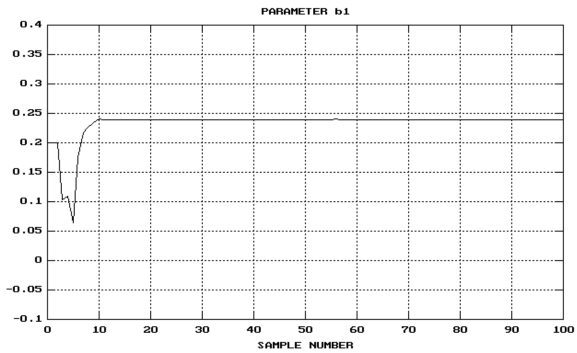

Fig. 10. Estimate of process parameter b_1.

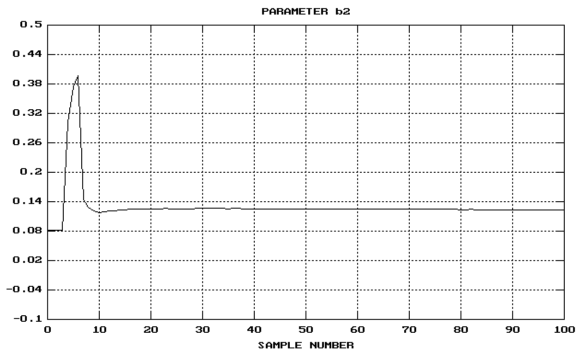

Fig. 11. Estimate of process parameter b_2.

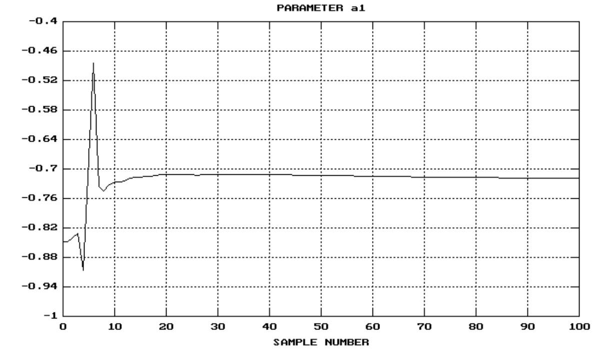

Fig. 12. Estimate of process parameter a_1.

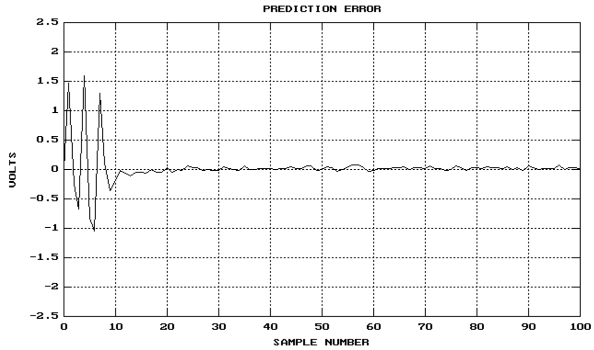

Fig. 13. Prediction error ε.

The controller parameters, computed from (21), are shown in Fig. 14 to Fig. 18. Since the process was neither subjected to changes on its dynamics nor subjected to external disturbances, the controller parameters converged to specific values. The parameter K_2 is identically null just because the closed loop polynomial in (24) was chosen with $t_5 = 0$, leading to $K_2 = 0$ in (20). Since K_2 is the derivative gain of the PID controller, $K_2 = 0$ means that the controller is actually a PI controller.

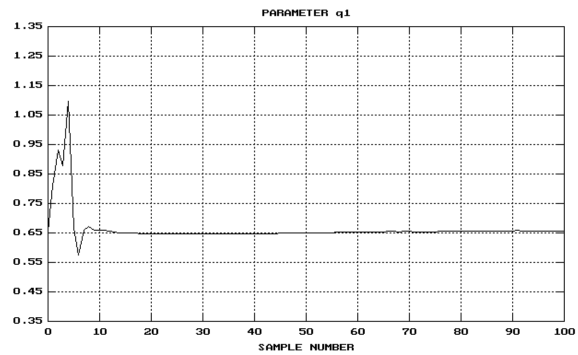

Fig. 14. Controller parameter q_1.

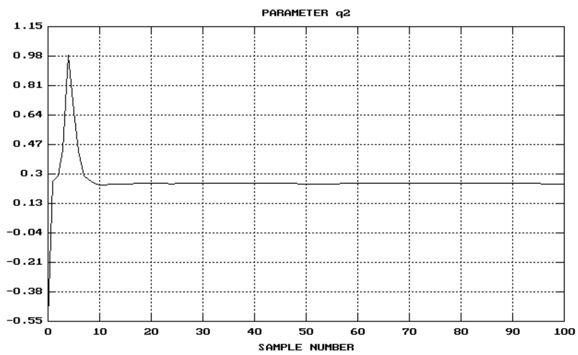

Fig. 15. Controller parameter q_2.

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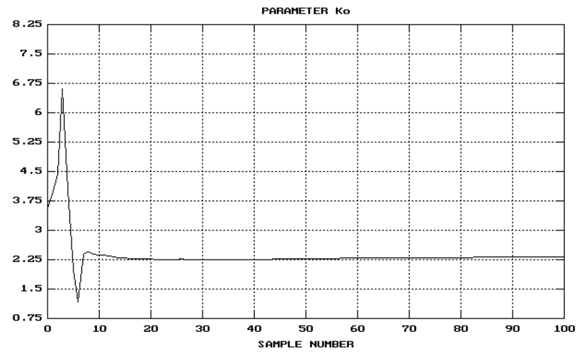

Fig. 16. Controller parameter K_0.

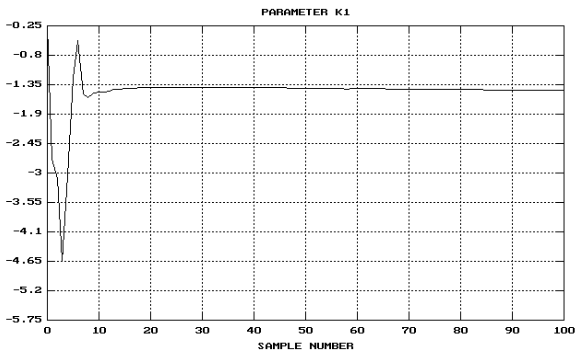

Fig. 17. Controller parameter K_1.

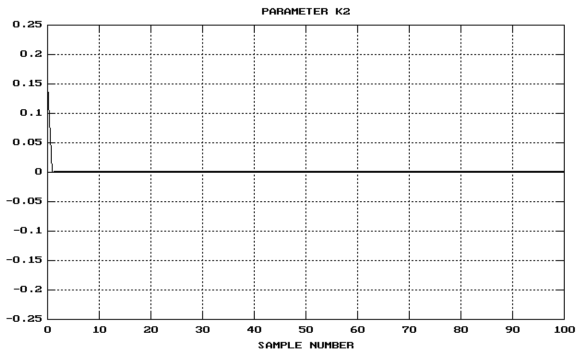

Fig. 18. Controller parameter K_2.

A. Performance in the presence of a dynamical change

To evaluate the ability of the adaptive controller to deal with changes in the process dynamics, an intentional disturbance was induced on the PT-326 system by quickly moving its temperature probe to another port of the duct.

Refer to Fig. 19. The system received a reference step input $\boldsymbol{r(k)}$ **= 15 ºC** (4.70 volts), as done in the previous test, and reached a steady state at around sample time k=12. Then, at sample time k=50, its temperature probe was removed from the central port (140 mm) and inserted into the right port of the duct (279 mm). This relocation of the sensor probe lasted 10 sample times (from k=50 to k=60) or 2 sec, since T=0.2 sec. The effect was a **change in the dynamics of the thermal process**. When the temperature probe was removed from the duct, it sensed the colder temperature of the external ambient air, so that the "process output" quickly dropped. When the probe is inserted again into the duct (now at its right port), it sensed the warmer temperature of the airflow, and "process output" quickly increased. This was a very intensive disturbance, as it caused a peak-to-peak variation of about 56,5% (3,67 volts) in the system output relatively to its steady state value before the disturbance occurs (6,5 volts).

Relocating the sensor probe caused changes in the process parameters, which were tracked by the system identification (Fig. 22 to Fig. 25), allowing the self-tuning of the controller parameters (Fig. 27 to Fig. 31). At the beginning of the disturbance, the prediction error (Fig. 26) became high due to the changes in the process dynamics, but it was gradually reduced as the parameter estimates were updated by the recursive identification and converged to the new process dynamics. The ability of the recursive identification to track the changes in the process dynamics is clearly shown in Fig. 22 to Fig. 25.

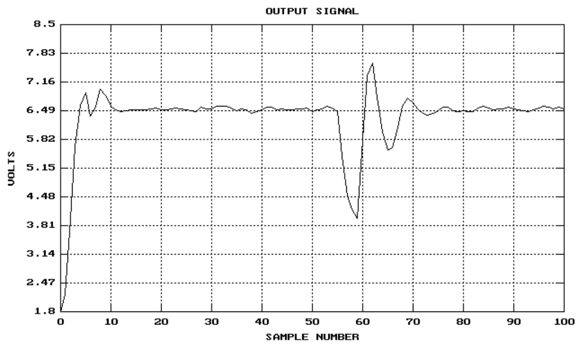

Fig. 19. Step response before and after a dynamical change in the process.

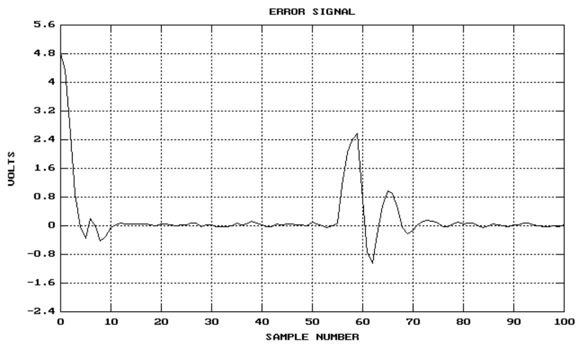

Fig. 20. Error of the step response.

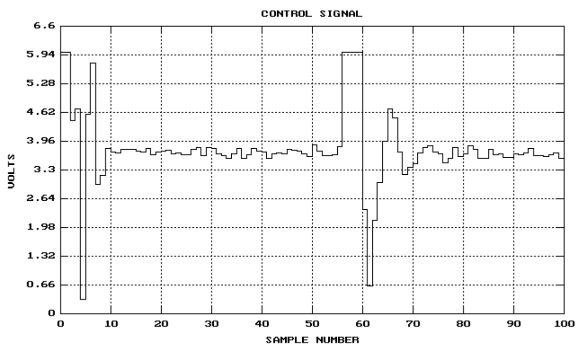

Fig. 21. Control signal.

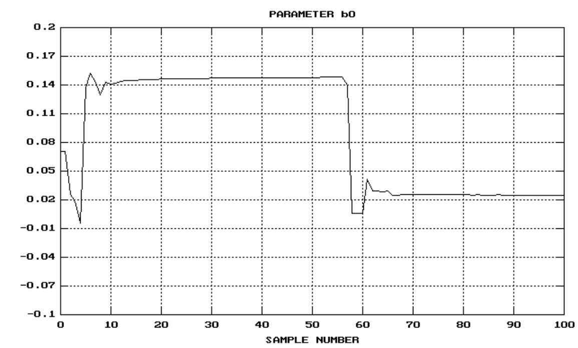

Fig. 22. Process parameter b_0.

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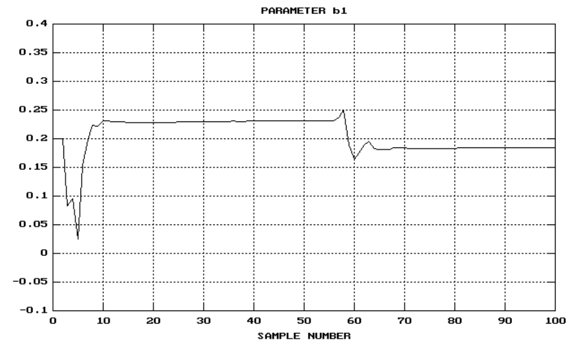

Fig. 23. Process parameter b_1.

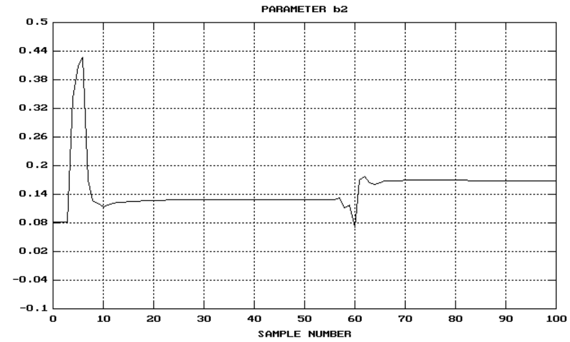

Fig. 24. Process parameter b_2.

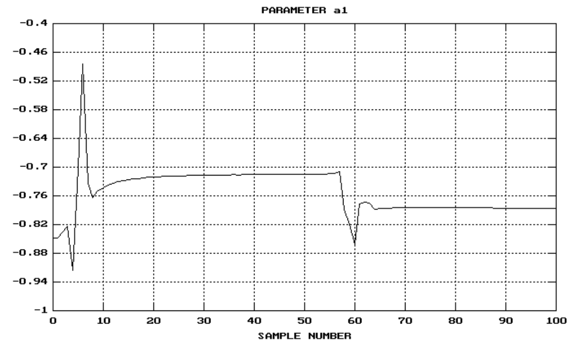

Fig. 25. Process parameter a_1.

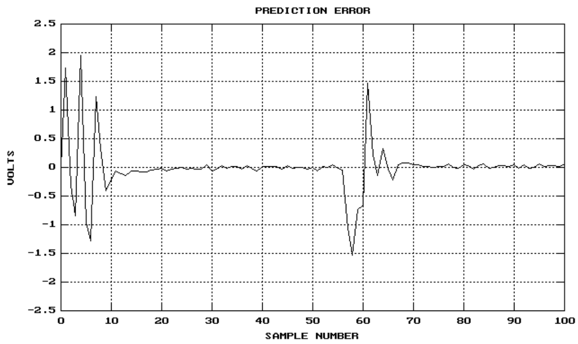

Fig. 26. Prediction error.

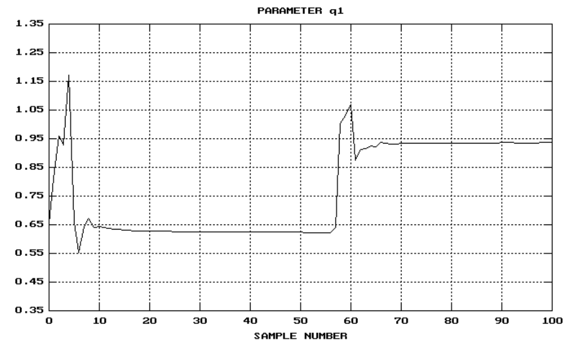

Fig. 27. Controller parameter q_1.

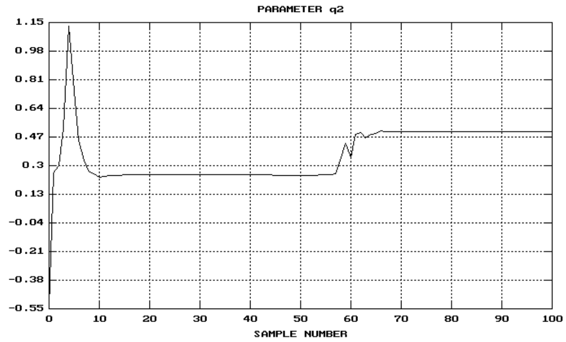

Fig. 28. Controller parameter q_2.

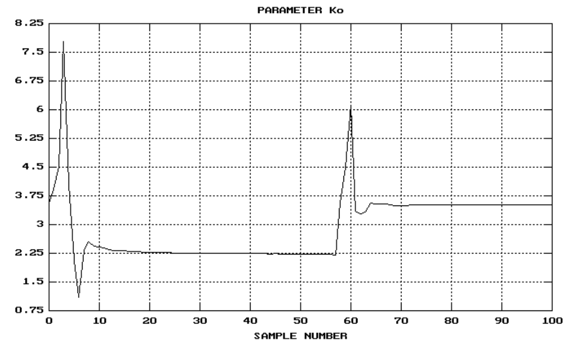

Fig. 29. Controller parameter K_0.

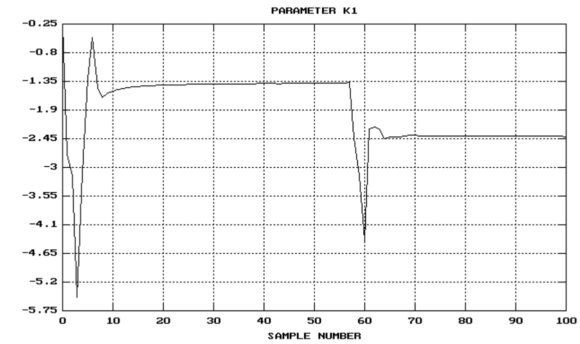

Fig. 30. Controller parameter K_1.

Notice that the controller parameter K_2 is identically null as in the previous test, for the same reason explained earlier.

As mentioned before, the relocation of the sensor probe lasted from sample time k=50 up to k=60. The controller fully compensated the disturbance around sample k=72, that is, in 2.4 sec after the end of the disturbance in the sensor probe. This is a fast adaptation ability.

Based on all these performance results, the adaptive self-tuning controller designed for the PT-326 system was considered effective.

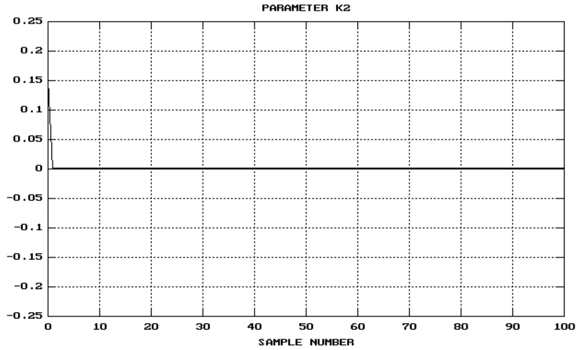

Fig. 31. Controller parameter K_2.

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VI. Conclusion

The practical results obtained in this work show that the use of adaptive self-tuning control with recursive identification of the process parameters provided excellent performance for the closed loop system. Although simpler classical (non-adaptive) control methods can also provide good performance, adaptive control is more advantageous in the presence of changes in the dynamics of the controlled process.

For the practical application described in this work, the airflow temperature of the PT-326 system was successfully regulated at the intended reference value, due to the ability of the controller to eliminate the steady state error in the temperature. Nevertheless, the major advantage of the adaptive controller was its effectiveness to compensate for changes in the process dynamics.

As a suggestion for further works, other methods for system identification (e.g.: maximum likelihood and instrumental variables), as well as for adaptive control (e.g.: minimum variance control, gain-scheduling control, and model reference adaptive control – MRAC) can be applied to the PT-326 system.

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