A Set of Identification and Control Design Methods for an Industrial Air Heating Process with Time-Delay: Stability Analysis and Design Specifications

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***Abstract*—This paper presents a set of real-time system identification and feedback control schemes for an industrial air heating process with time delay. Continuous time parametric model is obtained by using graphical based methods which are known process reaction curves. Discrete-time system model is obtained by employing online identification methods based on recursive extended least squares. The models are employed in elaborated feedback control schemes. A predictive proportional integral (PI) control and Smith predictor scheme, which can be employed for delay system, are presented. Stability characterization is addressed. A performance comparison between Smith Predictor and the Predictive PI controller is presented. The problems chosen for prototyping time delay control strategies are also widely used benchmark problems of control theory and this aspect of the paper makes it a beneficial guide to a large number of readers.**

***Index Terms*—system identification, recursive least squares, predictive PI control, smith predictor, stability analysis.**

I. Introduction

Time delay systems have been encountered in various applications across different areas such as; robotics, electrical networks, wireless transmission of sensor data's, congestion control in communication networks, traffic-flow and car following models, distributed and cooperative control for the coordination of unmanned vehicles, adaptive combustion control, haptics interfaces and motion synchronization, and biological systems as cell/virus dynamics [1]. The sources of delay phenomena can be summarized as follows [2]:

i) The time required for transferring energy, information and mass.
ii) The time required for processing and implementing for complicated control algorithm.
iii) The time required data processing, noninstantaneous communication, and computational limitations.

Systems, which represent such characteristics are also called hereditary, dead-time or aftereffect systems. In such systems, the variation of system state depends not only its present value, but also its past, since processes take effect after a certain amount of time elapses which follows the input [1]-[2].

The effects of time delays on closed-loop system are indisputable. As a first effect, they cause a physical constraint which does not allow reacting until periods of time after the change in the value of the state [2]. Secondly delays deteriorate the closed-loop transient response and decrease the phase margin of the system. In addition to the aforementioned effects, delays give rise to a quasi-polynomial characteristic equation which has infinitely many roots. These properties make the time delay systems very attractive to analyze and control, hence there have been numerous papers over the last decades dedicated to overcome these problems. The effects, if not taken into account, may cause significant problems such as undesirable and poor performance, instability and difficulties in controller design. Due to the aforementioned reasons the effects of time delay should be analyzed carefully both in the stability analysis and controller design.

The analysis of delay effects and designing stabilize controller is a tedious task. During the last few decades, developing different control strategies for time delay systems has drawn a great interest. One of the most fundamental control strategy for time delay systems is indisputably Smith Predictor, which is one of the most important dead-time compensator. Up to date, there have been various modifications of the Smith Predictor with similar ideas. For instance, a modification of the Smith predictor for FOPDT processes (First Order Plus Dead Time) is Predictive PI controller [3]-[4]. In this approach,

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the derivative term has been replaced by the predictive control term [5]-[6].

This paper is organized as follows. The second section presents the proposed system identification toolbox and continuous and discrete parametric models of the system. The next section is devoted to control strategies constructed on Smith predictors and predictive PI controllers. Furthermore, the stability analysis of predictive PI controller is addressed. The comparative analysis and assessments of the controllers are described in the last section and the concluding remarks are given at the end of the paper.

II. System Description and Real-Time Identification Through an Interactive Graphical User Interface (GUI)

The elaborated system is a temperature control training unit which consists of an air tube, heating element, temperature sensor and an air damper as depicted in Fig. 1. A thermistor, which is attached to the tube to sense the temperature of the air, can be inserted at three different locations in the tube enabling different transport delays [7]. The air flow in the tube can be changed by the manipulation of throttle opening. The main advantage of the system is to enable the study of several effects such as: time delays, hysteresis, saturation, transfer lags, PI or PID control and nonlinear effects in the control action. In order to achieve real time implementation, the experimental set-ups are linked to the computers via NI-PCI-6229 data acquisition board with National Instrument Company which is a multifunction data acquisition card having 32 analogue input- 16 analogue output, 48 Digital I/O, 250Ks/s-16 bit maximum sampling rate and resolution.

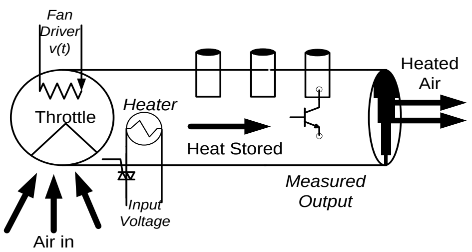

Figure 1. The structure of air heating process

So far, derivation of mathematical model of heating process is highlighted in several studies, hence it is not proposed to explain derivation of the dynamic model deeply in this study. Readers are referred to some studies for understanding the modelling of heating process [7].

During the identification of dead-time process, designer has to overcome two main problems. Firstly, the delay has to be identified, secondly the parameters of transfer function has to obtain properly.

A. Identification with Process Reaction Curve Methods

The central notion of the method is applying an open loop step test that is frequently used for analyzing of dynamical systems in control theory. In this experiment, a step signal with different amplitudes is applied to the selected system then process reaction curve is analyzed graphically to estimate the model parameters. The system is allowed to reach steady state in order to generate an accurate process reaction curve. A typical process reaction curve is depicted in Fig. 2. The elaborated methods are; first order method (FOM), First order plus dead time method (FOPDTM) and second order Harriott's method (SOHM) [7].

Yet another sufficient system characterization method is well known one is called first order plus dead time method. The transfer function of FOPDTM can be presented in (1).

$$G(s)=\frac{Ke^{-t_d s}}{\tau_p s+1}\approx\frac{K}{(\tau_p s+1).(t_d s+1)} \qquad (1)$$

In the proposed method two key point is introduced by t_d and τ_p are calculated by (2).

$$\begin{aligned} t_d &= 1.3t_{35.3}-0.29t_{85.3} \\ \tau_p &= 0.67(t_{85.3}-t_{35.3}) \end{aligned} \qquad (2)$$

The model parameters K, τ_p, t_d and transfer function of a FOPDT model is given in (3)

$$\frac{Y(s)}{U(s)}=0.61\frac{e^{-0.54s}}{1+1.57s} \qquad (3)$$

The response of the model which is obtained by using area methods [2] is presented in Fig. 2.

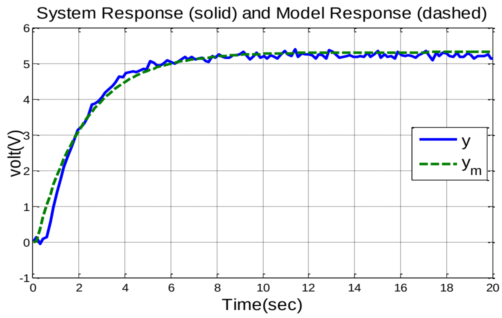

Figure 2. Model response and actual system response

Continuous time system transfer function which is obtained by using proposed real-time identification toolbox is given in Table.1. During the identification experiment a second order transfer function which can reflect the actual plant sufficiently close, is selected.

B. Real-time Online Identification Methods

This section covers, determining appropriate initial variables for an accurate estimation, analyzing the estimation of the model parameters via process reaction online identification based on recursive methods such as; Recursive least squares (RLS) [8-9]. The main goal is analyzing the computational complexity and accuracy of RLS to estimate the time delay, observing the effects of forgetting factor and how regulates the trade-off fast reaction and accuracy. Although recursive least squares have similar properties with their counterparts in 'batch' or off-line least squares setting, the method is a popular technique displaying several prominent features such as easy numerical solutions and fast parameter convergence.

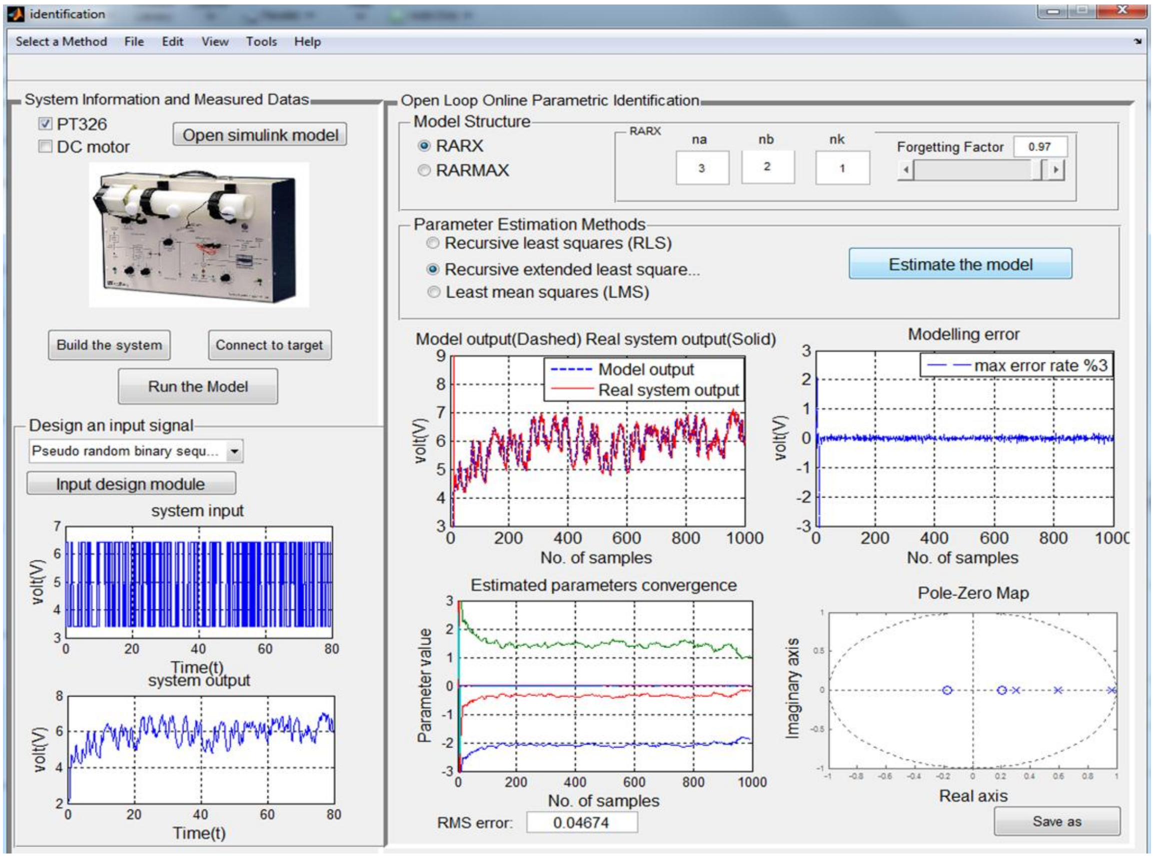

Figure 3. System identification toolbox and online identification screen shot

The key point about estimation of accurate model parameters is based upon the selection of sampling time that should be fast enough relative to the plant dynamics. Otherwise, unsuitable choice of the sampling interval may cause small plant gain, aliasing and stability problems [9]. However, a higher order model can be chosen, but it is worth mentioning that controller design for high order model will be a tedious task. The time delay models are obtained separately from an offline and online identification using least squares based methods and recursive least squares based methods.

The approach also gives consistent modeling accuracy over a wide range of operating conditions and seems the best linear estimation method [9]. For system identification, a pseudo random binary sequence is applied to the process and, input-output is recorded with a sampling time of 0.08 sec as shown in Fig. 3.

TABLE I. DISCRETE MODEL OF THE SYSTEM

Model order	Discrete Model and Corresponding Transfer Function
2.order	$G_1(z^{-1}) = \dfrac{0.009264\ z^{-1}}{1 - 1.807\ z^{-1} + 0.8145\ z^{-2}} z^{-1}$
3.order	$G_2(z^{-1}) = \dfrac{0.007855\ z^{-2}}{1 - 2.091\ z^{-1} + 1.439\ z^{-2} - 0.341\ z^{-3}} z^{-2}$

III. PREDICTIVE PROPORTIONAL INTEGRAL CONTROL OF DEAD-TIME PROCESS: STABILITY ANALYSIS

Predictive PI controller, which can be considered as a modification of Smith predictor for FOPDT processes, has been investigated in many studies [10]-[11]. Predictive PI controller has some advantages. For instance, tuning a PPI controller is much simpler than a Smith predictor, since PPI has two parameters [7]. In addition, when a Smith predictor is employed for an integrating process designer has to make some modifications to avoid steady state control error for load disturbances while the PPI controller does not require any modification for integrating systems [3]-[7]. However, its stability analysis has not still received much attention, nor its tuning methods or performance specifications, which has been addressed only in the original paper. In this section, the stability of the predictive PI control loop is analyzed in detail and performance comparison with a SP is addressed on air heating system [3], [7], see Fig. 4.

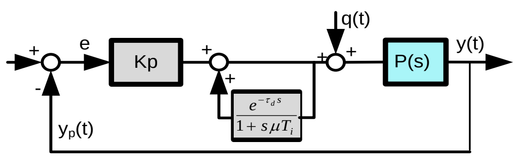

Figure 4. Predictive PI control block diagram

The transfer function of the PPI controller shows that a classical PI controller acts on the control error *e* and the prediction, due to the process model parametrization, is performed by low-pass filtering the control signal u. Hence, the transfer function of the PPI controller can be factorized as C_0C_{pred}, where C_0 is a PI controller and C_{pred} is a predictor structure as.

$$C_0 = K(1+\frac{1}{sT_i})\text{'}\, C_{pred} = \frac{1}{1+sT_i(1-e^{-\tau_d s})} \tag{4}$$

A. Stability Analysis

The Laplace transform of the controller and frequency Response is given as [3-6]:

$$G_c(s) = \frac{K_p(1+sT_i)}{1+s\mu T_i - e^{-\tau_d s}} \tag{5}$$

And

$$G(j\omega) = \frac{K}{1+T_p(j\omega)} e^{-j\omega\tau_d} = \sigma(\omega) + j\phi(\omega) \tag{6}$$

The controller output can be rewritten as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau - \mu \int_{t-L}^{t} u(\tau)d\tau \tag{7}$$

The Laplace transform can be represented as:

$$\frac{U(s)}{E(s)} = \frac{s}{s+\mu(1-e^{-\tau_d s})}(K_p + \frac{K_i}{s}) \tag{8}$$

where,

$$\frac{s}{s+\mu(1-e^{-\tau_d s})} := T(s,\mu,\tau_d) \tag{9}$$

The controller becomes a classical proportional-integral controller without $T(s,\mu,\tau_d)$ function, which can be considered a prediction filter. The frequency response of prediction filter is given [4-8].

$$T(j\omega) = \frac{\omega}{A} B \tag{10}$$

where;

$$A = \mu^2(1-\cos(\omega\tau_d))^2 + (\omega+\sin(\omega\tau_d))^2$$
$$B = ((\omega+\mu\sin(\omega\tau_d)) + j\mu(1-\cos(\omega\tau_d)) \tag{11}$$

The Nyquist stability criterion is given as:

$$\Re(G(j\omega)G_{PPI}(j\omega)) = -1,$$
$$\Im(G(j\omega)G_{PPI}(j\omega)) = 0 \tag{12}$$

where

$$G(j\omega) = \frac{K}{1+T_p(j\omega)} e^{-j\omega\tau_d},$$
$$G_{PPI}(j\omega) = T(j\omega)(K_p - j\frac{K_i}{\omega}) \tag{13}$$

With three unknown variables (K_p, K_i (T_i), μ) and two known parameters (ω,τ_d). To solve the PPI controller stability region with respect to controller parameters (K_p, K_i), the prediction gain μ is considered to be known. By the way, the stability conditions of the Predictor PI control system can be presents as follows [4]-[7].

$$K_p(\omega) = \frac{(\mu^2(1-\cos(\omega\tau_d))^2 + (\omega+\sin(\omega\tau_d))^2)\mathrm{N}(\omega)}{\mathrm{N}(\mathrm{N}^2(\omega)+\mathrm{H}^2(\omega))} \tag{14}$$

And

$$K_i(\omega) = \frac{-(\mu^2(1-\cos(\omega\tau_d))^2 + (\omega+\sin(\omega\tau_d))^2)\mathrm{H}(\omega)}{\mathrm{N}^2(\omega)+\mathrm{H}^2(\omega)} \tag{15}$$

where $N(\omega)$ and $H(\omega)$ are presented in (16) and (17)

$$\mathrm{N}(\omega) = \mu\sigma(\omega)(1-\cos(\omega\tau_d)) + \phi(\omega)(\omega+\mu\sin(\omega\tau_d)) \tag{16}$$

$$\mathrm{H}(\omega) = \mu\phi(1-\cos(\omega\tau_d)) - \sigma(\omega)(\omega+\mu\sin(\omega\tau_d)) \tag{17}$$

B. Investigating Parameter Effects and Design Specifications

In this section, the effects of the user defined controller parameters are investigated. Clearly the numbers of alternatives are infinitely many but the studied parameter sets describe the dynamically different regimes and their effects on the measurable performance metrics. We consider integral of the absolute error and integral squared error given by:

$$IAE = \int |e(t)|dt, \quad ISE = \int e^2(t)dt \tag{18}$$

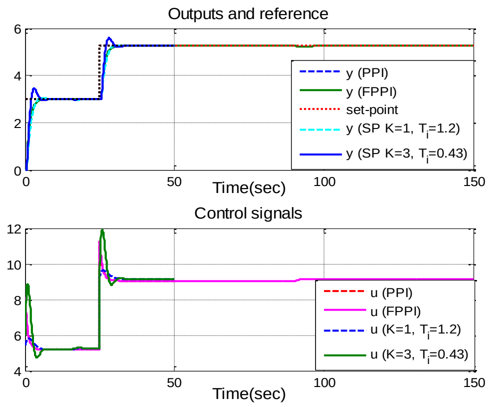

Figure 5. A Comparison of smith predictor and predictive PI controller on the system

The results of Predictive PI and Smith Predictor scheme are shown in Fig. 5, where it is seen that the control performance is obtained with satisfactory precision. Table II summarize the system performance for the two sets of controller parameters.

TABLE II. DISCRETE MODEL OF THE SYSTEM

Criterion	SET-1 (K=1, μ=0.98, T_i=1.2)	
	Predictive PI	SP
IAE	1.234	0.986
ISE	0.0873	0.0598
Criterion	SET-2 (K=3, μ=1.23, T_i=0.43)	
	Predictive PI	SP
IAE	1.458	1.897
ISE	0.1268	0.243

IV. CONCLUSION

The current paper describes a set of identification and control experiments to analysis the fundamental concepts of dead time control systems. In order to obtain an accurate model, identification methods are studied on a proposed system identification GUI. A Predictive PI controller is elaborated and stability conditions are described. The control scheme has been successfully applied to a hot air blower system. The performance investigations and design specifications are compared with Smith predictor control structure

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