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Closed-loop identification of wafer temperature dynamics in a rapid thermal process

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Abstract−Single wafer rapid thermal processing (RTP) can be used for various wafer fabrication steps such as annealing, oxidation and chemical vapor deposition. A key issue in RTP is accurate temperature control, i.e., the wafer temperatures should be rapidly increased while maintaining uniformity of the temperature profile. A closed-loop identification method that suppresses RTP drift effects and maintains a linear operating region during identification tests is proposed. A simple graphical identification method that can be implemented on a field controller for autotuning and a nonlinear least squares method have been investigated. Both methods are tested with RTP equipment based on a design developed by Texas Instruments.

Key words: Rapid Thermal Process, Wafer Temperature, Closed-loop Identification, First Order Plus Time Delay Model

INTRODUCTION

The rapid thermal processing (RTP) method is an important manufacturing technology for wafer fabrication processes such as annealing, oxidation, chemical vapor deposition and cleaning. RTP systems can conduct these operations with a reduced thermal budget compared to multiwafer systems such as a diffusion furnace. A key requirement for the RTP system is to maintain a uniform temperature profile on the wafer while following fast temperature trajectories [Huang et al., 2000]. The tracking problem becomes more difficult as the radius of wafer is increased for higher productivity of wafer fabrication. Several approaches have been proposed for temperature control of RTP systems, e.g., multivariable internal model control [Schaper et al., 1994], adaptive control [Choi et al., 2003], iterative learning control [Lee et al., 2001; Choi et al., 2001] and decentralized control [Cho et al., 1994; Schaper et al., 1999]. Each method has its own tuning parameters, but advanced control systems tuned loosely sometimes perform worse than simple control systems tuned well. Because operating environments of RTP systems can be variable, it is desirable for control systems to be simple to tune. Decentralized control with a steady-state model [Schaper et al., 1999] and multivariable proportional-integral (PI) control [Lin and Jan, 2001] are two representative approaches.

In this paper, we propose a single-input single-output (SISO) identification method to tune simple control systems for RTP processes. Wafer temperature signals are corrupted with electromagnetic noise from high-power electric circuits and thermal noise from tungsten-halogen lamps. Furthermore, considerable drift can occur due to the large thermal masses of the chamber wall, and quartz windows are found. These factors make open-loop and multivariable identification of RTP processes difficult to perform, leading to inaccurate models. The wafer temperature ramps up and goes outside of the linear region during open-loop tests. When these drift effects are not removed, the identified multivariable models can be very inaccurate. Here, a closed-loop SISO identification method is applied to overcome drifting temperature signals. With closed-loop tests, the wafer temperatures are kept in a linear operating region for longer test runs [Yeo et al., 2004], drift effects are easily removed, and repeatable experimental results can be obtained.

Drift can be assumed to be linear if an identification experiment is short enough in duration. So, in the usual open-loop step test, the drift effect can be removed from experimental data simply by finding the slope of drift and subtracting the drift component. But it is difficult to find the slope of drift when experimental data are corrupted with noise. A nonlinear least squares method can be used by including one additional variable for the linear drift. Here we propose a simple identification method which uses PI control for the identification experiment, allowing an accurate low order model to be computed for processes with a linear ramp drift.

Besides RTP systems, there are processes with drifts whose characteristics are difficult to model. For example, some chemical processes can take a long time to reach their steady states from start-up or from environmental upsets. Before they settle down to steady states, their input-output behaviors can exhibit slow drift. The proposed method can also be applied to these drifting processes and used to tune PID controllers automatically without waiting for the process to reach steady states.

1. Experimental Rapid Thermal Processor

1-1. Experimental Setup

The experimental RTP equipment design used in this study was developed by Texas Instrument (Dallas, Texas) to fabricate 6-in wafers. The main chamber is shown in Fig. 1. Three circular groups of Tungsten-Halogen lamps are used to heat up the wafer. Fig. 2 shows a detailed schematic, with a half-inch thick, 10 inch diameter quartz plate and the 6 inch wafer inside the cold-wall reactor. The edge lamp zone consists of 24 lamps (1 KW in total), the middle lamp zone consists of 12 lamps (1 KW in total) and one 2 KW lamp is in the center. The reflector is covered with gold-plated material to enhance the light reflection. The lamp housing is cooled by water continuously. Each group of lamps can be manipulated independently.

The wafer temperature is measured with K-type thermocouples

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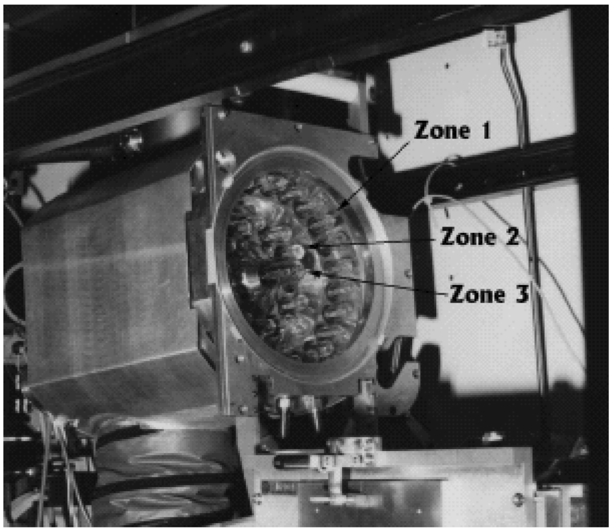

Fig. 1. Picture of the experimental RTP system.

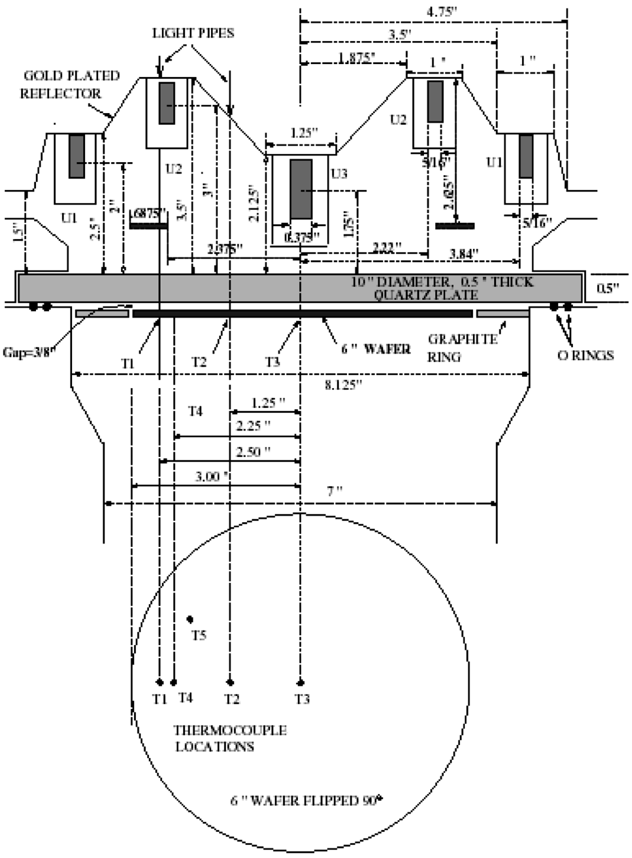

Fig. 2. Schematic for the experimental RTP chamber.

buried on the wafer (Fig. 2) and is controlled with a personal computer and TI 545 PLC. Details about the RTP system are found in Cho [2005]. By choosing three temperature measurements, a 3×3 multi-input multi-output (MIMO) system can be designed. One control system for the RTP system is an SISO control system with a power distribution network as shown in Fig. 3(a). By adjusting the power distribution network gains, k_1, k_2 and k_3, temperature uniformity can be obtained. A gain scheduling technique was used to adjust the power distribution network gains.

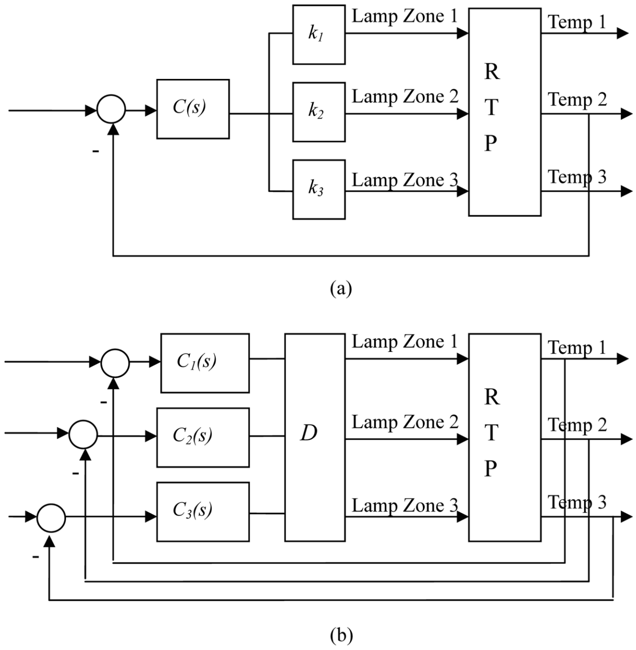

Fig. 3. (a) Conventional SISO control Temperature 2 for the RTP system. (b) Decentralized control with a static decoupler D.

To design a model-based control system, dynamic models for this system have been developed. A general model for this RTP system is given by

$$\dot{\overline{T}}(t) = F(\overline{T}(t)) + G(\overline{T}(t))\overline{P}(t) + D(t) \tag{1}$$

where $\overline{T}=[T_1, T_2, \cdots, T_n]^T$ is a vector of temperature measurements, $\overline{P}=[P_1, P_2, \cdots, P_m]^T$ is the lamp power vector, $T(\overline{T}(t))$ and $G(\overline{T}(t))$ are matrices of nonlinear functions of temperatures and D(t) includes unmodeled dynamics such as drift. Based on this model with the assumption that $|G_{ii}(\overline{T})|>>|G_{ij}(\overline{T})|$, $i\neq j$, Choi et al. [2003] proposed a decentralized adaptive control system. Under the assumption of diagonal dominance, a decentralized control system can be used to control the RTP system of Eq. (1). When this assumption is not met, we may use a static decoupler as shown in Fig. 3(b).

SISO tuning methods can be applied directly to the control system of Fig. 3(a). The sequential loop closing method [Koo et al., 2004] can be used to design the multiloop control systems of Fig. 3(b), where each controller $C_i(s)$ is designed by SISO methods sequentially. SISO tuning methods can be applied for either control system in Fig. 3, by using SISO identification methods to treat processes with drifts.

2. Open-loop Step Response

When a wafer is heated by tungsten-halogen lamps, the wall of the RTP process chamber and quartz window dividing the wafer chamber and lamp zones are also heated up. The time constant of the wafer is usually around 10 sec. On the other hand, time constants of the wall and quartz window are on the order of 100 sec due to their large thermal mass. Hence slow dynamics of the wall and the quartz window are added to the dynamics of the wafer as a drift. Fig. 4 shows an experimental open-loop step response at the wafer temperature 300 °C and shows this effect.

Assuming drift is a linear function of time during an identification

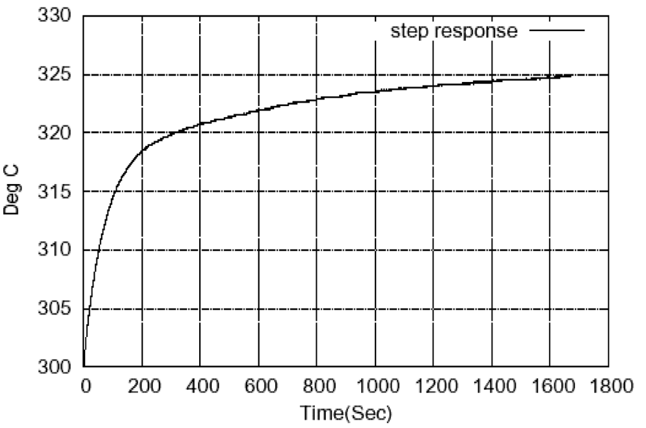

Fig. 4. Typical open-loop step responses of wafer temperatures to a step increase in the lamp power.

step test, a step response for the wafer dynamics can be expressed as

$$T(t)=T_p(t)+T_d(t) \tag{2}$$

where T(t) is the measured wafer temperature, $T_p(t)$ and $T_d(t)$ are wafer temperature components due to the manipulated variable (lamp power) and drift, respectively. The Laplace transform of T(t) is

$$T(s)=T_p(s)+T_d(s)=G_p(s)P(s)+T_d(s) \tag{3}$$

where $G_p(s)$ is a transfer function between the wafer temperature and the power input P(s). The drift component $T_d(s)$ will hinder obtaining the process transfer function $G_p(s)$; thus a detrending step is needed to elucidate $G_p(s)$.

As shown in Fig. 4, it is difficult to maintain the operating state under open-loop conditions. In addition, the detrending step can cause inaccuracies in identified parameters when measurements are corrupted with noise.

3. Closed-loop Identification with a PI Controller

To reduce the effects of drift, a closed-loop identification method is investigated to obtain a process transfer function model

$$G_p(s)=\frac{K_p\exp(-\theta_p s)}{\tau_p s+1} \tag{4}$$

For the closed-loop test, a PI controller

$$G_c(s)=K_c\left(1+\frac{1}{\tau_I s}\right) \tag{5}$$

is used.

Since $P(s)=G_c(s)(R(s)-T(s))$, for a ramp drift with a slope of α (its Laplace transform is α/s^2), the closed-loop system becomes

$$T(s)=T_r(s)+T_d(s)=\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}R(s)+\frac{1}{1+G_c(s)G_p(s)}\frac{\alpha}{s^2} \tag{6}$$

where $T_r(s)$ and $T_d(s)$ are Laplace transformations of drift-free and drift components, respectively. This equation shows that, under a closed-loop environment, the drift term becomes

$$T_d(s)\equiv\frac{\alpha}{s(1+sG_c(s)G_p(s))} \tag{7}$$

For a linear drift, the asymptotic (long time) value is $T_d(t)|_{t\to\infty}=sT_d(s)|_{s=0}=\alpha K_c K_p/\tau_I$. When the step set point change is given after $T_d(t)$ approaches a constant ramp, we can obtain the component without drift simply by subtracting a constant value of $T_d(t)|_{t\to\infty}$.

3-1. Graphical Method

When the wafer temperature shows an oscillatory response, we can obtain the process model parameters easily with a simple graphical method. First, subtracting the asymptotic slope of the drift component $T_d(t)$, we can obtain the drift-free temperature. As shown in Fig. 5, we find the time delay term θ_p. Then, by calculating the decay ratio and the period of oscillation, we obtain an approximate second order plus time delay model of the closed-loop system as

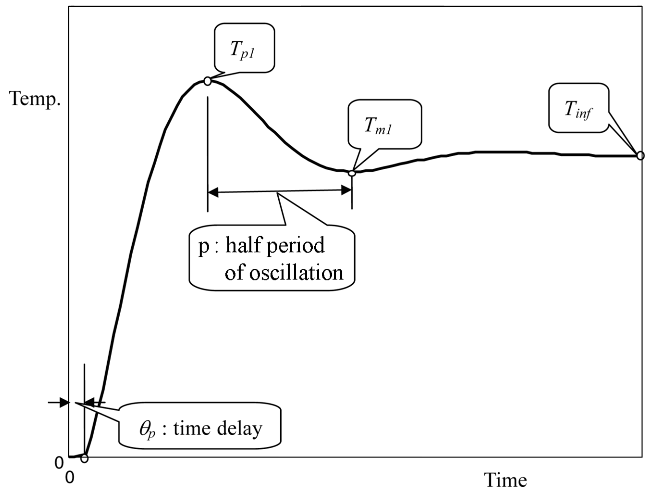

Fig. 5. Graphical method for closed-loop identification.

$$T_r(s)\approx\frac{\exp(-\theta_p s)}{\tau_{cl}^2 s^2+2\zeta_{cl}\tau_{cl}s+1}R(s) \tag{8}$$

where

$$\delta=\left(\frac{T_{p1}-\Delta r}{\Delta r}+\frac{\Delta r-T_{m1}}{T_{p1}-\Delta r}\right)/2$$

$$\zeta_{cl}=-\ln(\delta)/\sqrt{\pi^2+\ln^2(\delta)}$$

$$\tau_{cl}=p\frac{\sqrt{1-\zeta_{cl}^2}}{\pi}$$

Δr=size of the set point change

T_{p1}, T_{m1}=the first peak and minimum of $T_r(t)$

p=half of the period of oscillation

By matching dominant poles in Eqs. (6) and (8) [Lee, 1989; Seborg et al., 2004], we can obtain the process parameters τ_p and K_p such that $\tau_p s^2+s+(K_c s+K_c/\tau_I)K_p e^{-\theta_p s}|_{s=-\sigma\pm j\omega}=0$, where $\sigma=\zeta_{cl}/\tau_{cl}$ and $\omega=\sqrt{1-\zeta_{c1}^2}/\tau_{cl}$. The solution is

$$\begin{bmatrix}\mathrm{Re}((K_c s+K_c/\tau_I)\exp(-\theta_p s)) & \mathrm{Re}(s^2)\\ \mathrm{Im}((K_c s+K_c/\tau_I)\exp(-\theta_p s)) & \mathrm{Im}(s^2)\end{bmatrix}\begin{bmatrix}K_p\\ \tau_p\end{bmatrix}=-\begin{bmatrix}\mathrm{Re}(s)\\ \mathrm{Im}(s)\end{bmatrix}_{s=-\sigma+j\omega} \tag{9}$$

where Re(.) and Im(.) mean the real and imaginary parts of a complex number, respectively.

3-2. Nonlinear Least Squares Method

Nonlinear least squares method can also be applied to extract the process model parameters from closed-loop responses with drift. Consider an error squared function

$$J = \int_0^{t_f} |T(t) - T_m(t)|^2 dt \quad (10)$$

where

$$T_m(t) = L^{-1}\left(\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}R(s)\right) + \alpha t$$

$L^{-1}(\bullet)$: inverse Laplace transformation

The minimum of Eq. (10) is searched for the process model parameters, K_p, τ_p and θ_p of $G_p(s)=K_p\exp(-\theta_p s)/\tau_p s+1$ and the drift parameter, α.

This nonlinear least squares method can also be applied to non-oscillatory responses. To solve the above nonlinear optimization problem, we used the MATLAB routine, 'constr', which is based on successive quadratic programming [Edgar et al., 2001].

EXPERIMENTAL RESULTS

Identification experiments were performed for various temperature levels and closed-loop PI control parameters. Fig. 6 shows typical responses for a temperature level of around 600 °C (it is difficult to set the operating condition exactly due to varying drifts), and Table 1 shows identification results.

Compared to the nonlinear least squares method, the graphical identification method provides somewhat scattered model parameters for K_p and τ_p. Fig. 6 compares experimental closed-loop responses and predictions for the model obtained from data of Run 3, which show excellent agreement. With the averaged model parameters for the graphical method, we designed a PI control system as K_c= 3.31 and τ_I=11.54 (the tuning method of Lee et al. [1998] is used) and applied to all models in Table 1 identified by the graphical method. Fig. 7 shows that the control system designed by the averaged model parameters is acceptable.

The nonlinear least squares method provides better model parameters when variations are small. Fig. 8 compares experimental closed-

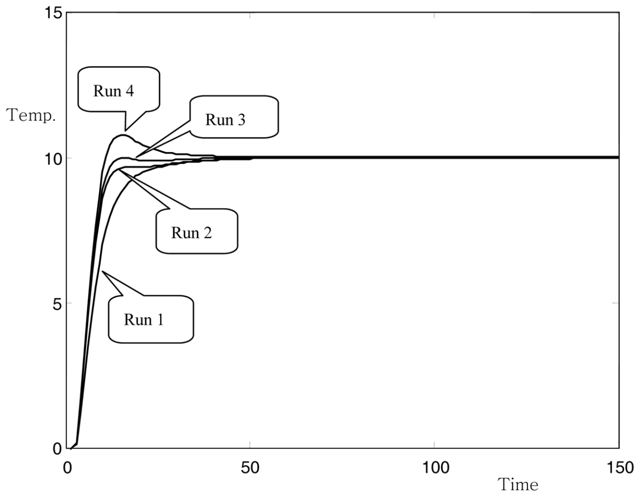

Fig. 7. Set-point responses of the PI control system with K_c=3.31 and τ_I=11.54 for models in Table 1 identified by the nonlinear least squares method.

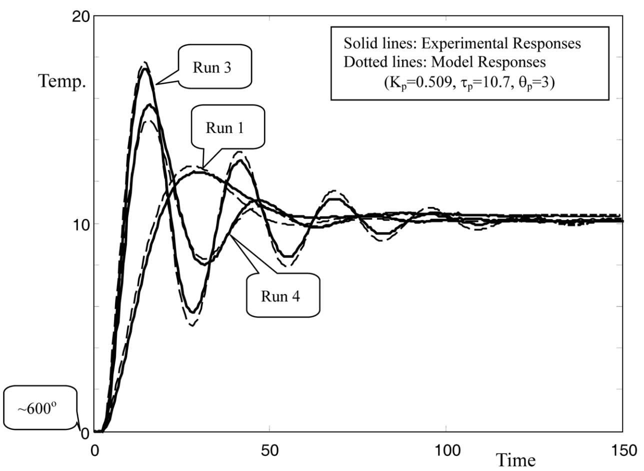

Fig. 6. Closed-loop responses of PI control systems. The model obtained from Run 3 with the graphical method is used for model responses.

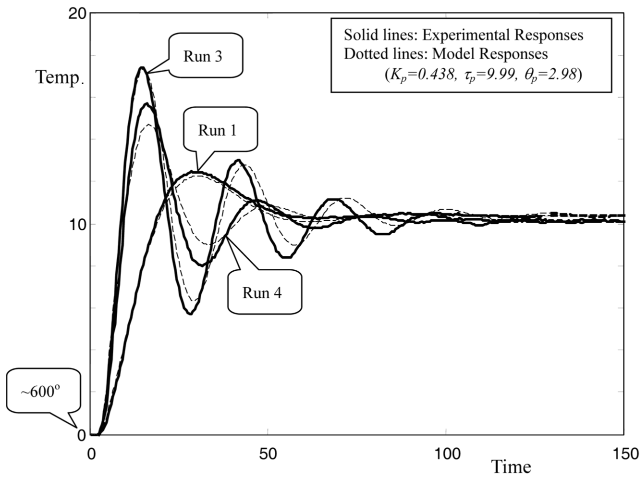

Fig. 8. Closed-loop responses of PI control systems. The model obtained from Run 1 with the nonlinear least squares method is used for model responses.

Table 1. Identification results

Test number	PI control parameters	Identified FOPTD model (simple graphical method)	Identified FOPTD model (least squares method)
Run 1 (Jun. 18)	K_c=1, τ_I=3.6	K_p=0.374, τ_p=10.44, θ_p=3	K_p=0.438, τ_p=9.99, θ_p=2.98
Run 2 (Jun. 22)	K_c=1, τ_I=3.6	K_p=0.459, τ_p=9.71, θ_p=3	K_p=0.448, τ_p=8.72, θ_p=3.26
Run 3 (Jun. 24)	K_c=2.5, τ_I=2.52	K_p=0.509, τ_p=10.70, θ_p=3	(not calculated)
Run 4 (Jun. 25)	K_c=2.5, τ_I=3.6	K_p=0.650, τ_p=13.51, θ_p=3	K_p=0.438, τ_p=8.18, θ_p=3.44
Average		K_p=0.498, τ_p=11.90, θ_p=3	K_p=0.441, τ_p=8.96, θ_p=3.22

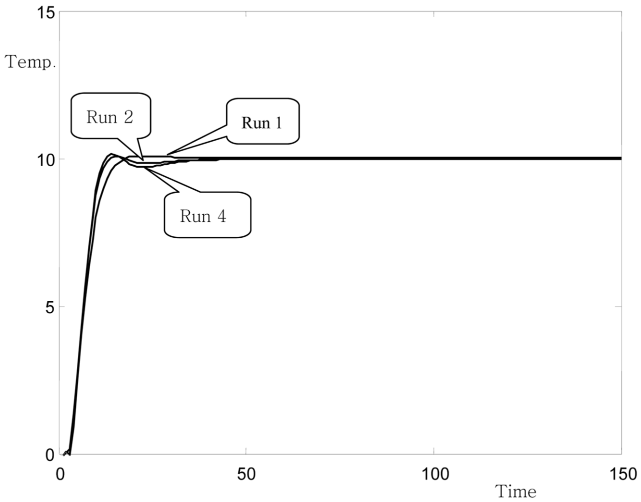

Fig. 9. Set-point responses of the PI control system with K_c=3.03 and τ_I=9.68 for models in Table 1 identified by the nonlinear least squares method.

loop responses and model responses obtained from data of Run 1. A PI control system with K_c=3.03, τ_I=9.68 can be obtained by applying the tuning method of Lee et al. [1998] to the averaged model parameters for the nonlinear least squares method. Fig. 9 shows closed-loop responses when the control system is applied to all models in Table 1 that are identified by the nonlinear least squares method.

CONCLUSIONS

Closed-loop identification methods are applied to an RTP system based on a design developed by Texas Instruments. Proportional-integral controllers are used to suppress drift effects during closed-loop identification and to maintain a linear operating region during identification tests. A simple graphical method and nonlinear least squares are investigated for model identification. Both methods provide reasonable model parameters which can be used to design control systems. The simple graphical method can be implemented easily on a field controller for autotuning. The nonlinear least squares method can be used to obtain better model parameters by using off-line calculations.

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