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Design of Uniform Temperature Controller based on Temperature Difference Model

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Abstract: Thermal distribution in manufacturing processes, which is observed in both steady and transient states, causes inferior quality. Thus, uniform temperature control is extremely required in many industrial application fields for quality improvement. Conventional control based on black box model is cheap for the control of thermal plant with strong interference. To deal with these problems, we have proposed the temperature difference model (TDM) for thermal process. In this paper, the design method of uniform temperature controller for two-dimensional heat plate is proposed. And the effectiveness of the proposed system is clarified by experiments.

1. INTRODUCTION

Recently, advanced manufacturing processes for flat panel displays and semiconductor devices, require highly accurate temperature control due to the demands of more miniaturization of circuit layout and larger of thermal operation areas. In addition, the temperature uniformity of heat plate have been required not only in the steady-state, but also in the transient state (Kailath (1999)).

To design control system of thermal process, black box modeling based on input-output signal has been mainly used, which implies that the physical properties of the controlled object are ignored in the modeling (Astrom (2005)). Hence, PID tuning based on such black box model will become complex due to lack of description ability of the model, and expertness is required to adjust transient responses of multivariable interference systems. The tuning know-how of PID controller is effective only on the physical construction, e.g. material constant, plate size, allocations of heaters and sensors, etc.. Therefore, it is difficult to apply these tuning know-how to various systems. On the other hand, it is well known that the thermal plate is typical distributed parameter system and has strong thermal interferences. So, a new model which represents physical characteristics, i.e. heat transfer and heat conduction, is of great significance.

To deal with these problems, we have proposed the temperature difference model (TDM) for thermal process (Nanno (2006)). The feature of the TDM is to represent thermal interference explicitly with the feedback temperature difference. The design methods of uniform temperature controller and decoupler based on one dimensional TDM were proposed and the effectiveness of these controller was demonstrated in experiments (Nanno (2007),Matsunaga (2005)). However, the control system for practical two dimensional heat plate has not been discussed yet.

The aims of our study is to construct the thermal controller focusing on the characteristics of advanced heat process. In this paper, the design method of uniform temperature controller based on a two dimensional TDM is proposed. First, the two dimensional TDM of the ideal heat plate is outlined. Secondly, the thermal interferences are enhanced by the temperature difference feedback. Furthermore, a set point regulator is designed based on the strongly coupled plant. Finally, uniform temperature control for a heat plate is evaluated by experiments.

2. THERMAL PROCESS MODEL WITH FEEDBACK STRUCTURE

2.1 Physical modeling of heat plate

For simplicity, it is assumed that the controlled object is composed of two small and homogeneous cells, and that there are no temperature distribution in each cell. Then the controlled object is considered as two lumped capacitance models as shown in Fig.1 (Nanno (2006)). As

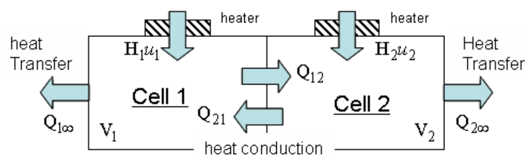


Fig. 1. Cell modeling of one dimensional heat plate

each cell is homogeneous with volume V_i, dynamics of the internal energy of the cell is described from the energy conservation law as

$$c\rho V_i \frac{d\theta_i}{dt} = -Q_{i\infty} - Q_{ij} + H_i u_i \tag{1}$$

where θ_i[K] is the cell temperature, c[J/(kg·K)] and ρ[kg/m^3] are the specific heat and density of the cell, u_i is the manipulated variable, and H_i[W/%] is the conversion coefficient from the duty ratio to heat power. $Q_{i\infty}$ is the heat flow by heat transfer from the surface of cell i to the atmosphere, Q_{ij} is the heat flow from cell i to cell j.

The heat flow Q_{ij} is given from Fourier's law as

$$Q_{ij} = -A_s \lambda \frac{\theta_j - \theta_i}{d} \tag{2}$$

where λ[W/m·K] is the thermal conductivity, $A_s[\mathrm{m}^2]$ is the cross sectional area, and d[m] is the distance between the heaters. And the heat flow $Q_{i\infty}$ is given from Newton's cooling law as

$$Q_{i\infty} = -A_i h_i(\theta_\infty - \theta_i) \tag{3}$$

where θ_∞ is the environmental temperature, $A_i[\mathrm{m}^2]$ and $h_i[\mathrm{W}/(\mathrm{m}^2{\cdot}\mathrm{K})]$ are the surface area and heat transfer coefficient of cell i, respectively. Since θ_∞ is the cell's environmental temperature, generality is not lost when it is assumed to be $0[^o\mathrm{C}]$.

From eqs.(1)-(3), we have a block diagram as shown in Fig.2. The transfer functions in the figure are as follows:

$$H_{si} = \frac{K_i}{1 + sT_i} \tag{4}$$

$$K_i = \frac{1}{\alpha_i}, \quad T_i = \frac{E_i}{\alpha_i}, \quad \beta = \frac{\lambda A_s}{d} \tag{5}$$

$$E_i = c\rho V_i, \quad \alpha_i = h_i A_i \tag{6}$$

It is well known that the heat plate is typical distributed system, and the dynamics of eq.(4) closes to that of distributed system in case that the division number by homogeneous cell tends to infinity. In that sense, the model in Fig.2 can be regarded as a low order approximation of distributed system. The feature of the approximated model is that the temperature difference is fed back to the input via β. We shall call this model "the temperature difference model (TDM)". Also, an attractive feature of the models is that the parameters of equation can be related to physical quantities such as volumes, heat flow and material constant.

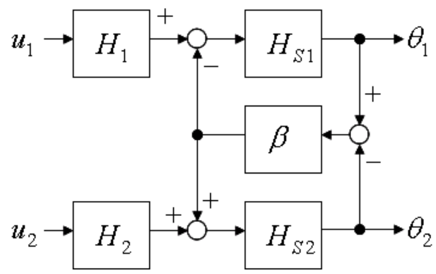


Fig. 2. Block diagram of one dimensional TDM

2.2 Two dimensional TDM

Let consider the simple two dimensional heat plate with 4 heaters as shown in Fig.3. In the figure, β_{ij} is thermal conduction from cell i and j. For example, the temperature θ_1 is represented as follows

$$\begin{aligned}\theta_1 = H_{s1}[(H_1 u_1 - \beta_{12}(\theta_1 - \theta_2) \\ - \beta_{13}(\theta_1 - \theta_3) - \beta_{14}(\theta_1 - \theta_4)]\end{aligned} \tag{7}$$

Fig.4 shows a block diagram of TDM for two dimensional heat plate. Similar description are obtained for a larger heat plate, but the number of thermal interference increases according to the number of heaters.

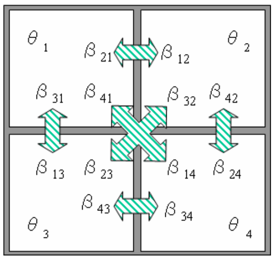


Fig. 3. Two dimensional heat plate

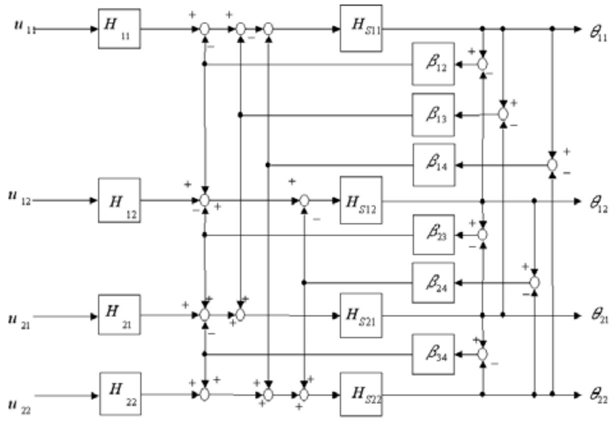


Fig. 4. Block diagram of two dimensional TDM

3. UNIFORM TEMPERATURE CONTROL FOR TWO DIMENSIONAL HEAT PLATE

It is difficult to design uniform temperature controller for MIMO system with thermal interferences. Traditionally, decoupling controller and SISO system design have been widely used in industrial applications. Paying attention to the temperature interference of the TDM, a novel uniform temperature controller can be design using cascade approach in the following two steps,

step 1) Design of the enhanced coupling controller in which the difference temperature between θ_i and θ_j is fed back to the input so that the thermal interference is strengthen and strongly coupled.

step 2) Design of the regulator based on the strongly coupled plant in **step 1)**.

3.1 Design of enhanced coupling controller

From **step 1)**, the enhanced coupling controller for CH1 is designed from Fig.4,

$$\begin{aligned}u_1 = v_1 + (L_1 H_1)^{-1}[(B_{12}(\theta_1 - \theta_2) \\ + B_{13}(\theta_1 - \theta_3) + B_{14}(\theta_1 - \theta_4)]\end{aligned} \tag{8}$$

where v_i is the new input to the controlled object and L_i is the linearizing compensator from input to heater output, $B_{ij}[W/K]$ is a feedback gain for the temperature difference $\theta_i - \theta_j$.

By setting $B_{ij} = \beta_{ij} - K_{pp}$, transfer function from v_i to θ_i is obtained as

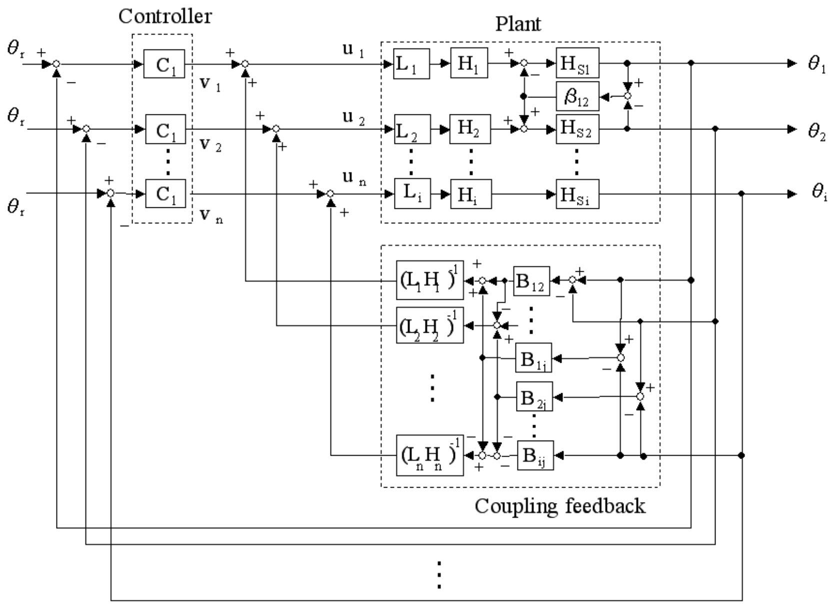


Fig. 5. Block diagram of temperature control system

$$\begin{bmatrix}\theta_1\\ \vdots\\ \theta_n\end{bmatrix}=\begin{bmatrix}G_{11} & \cdots & G_{1n}\\ \vdots & \ddots & \vdots\\ G_{n1} & \cdots & G_{nn}\end{bmatrix}\begin{bmatrix}v_1\\ \vdots\\ v_n\end{bmatrix} \quad (9)$$

where

$$G_{ii}=\frac{(T_j s + K_j K_{pp} + 1)K_i L_i H_i}{den(s)} \quad (10)$$

$$G_{ij}=\frac{K_i K_j K_{pp} L_i H_j}{den(s)} \quad (11)$$

$$: dens(s)=T_i T_j s^2 + [(1 + K_j K_{pp})T_i + (1 + K_i K_{pp})T_j]s + (K_i + K_j)K_{pp} + 1$$

By $K_{pp} \to \infty$, eq.(10) and eq.(11) are rewritten as

$$\lim_{K_{pp}\to\infty} G_{ii}=\frac{K_i L_i H_i}{(K_j T_i + K_i T_j)s + K_i + K_j} = \bar{G}_{ii} \quad (12)$$

$$\lim_{K_{pp}\to\infty} G_{ij}=\frac{L_j}{L_i}\frac{H_j}{H_i}\bar{G}_{ii} \quad (13)$$

Moreover, L_i is adjusted so that $L_i H_i = L_j H_j$, transfer functions from input v to output θ_i is obtained as

$$\theta_i = \bar{G}_{ii}\sum_{i=1}^{n} v_i \quad (14)$$

Since the thermal interferences are enhanced by the coupling gain K_{pp}, the transfer functions from $\sum v_i$ to θ_i are uniformed. This implies that the heat plate with enhanced coupling feedback can be regarded as a "ideal heat plate" made of the high heat conduction material.

3.2 Design of uniform temperature control based on TDM

Next, from **step 2)**, a setpoint regulator is designed for the strongly coupled plant. Simple set point regulator is designed as

$$v_i = C_1(r - \theta_i) \quad (15)$$

Substituting eq.(15) into eq.(8), we have following controller for two dimensional heat plate.

$$\begin{aligned}u_1 = &C_1(r - \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4}{4})\\ &+ [(L_1H_1)^{-1}B_{12} - \frac{C_1}{4}](\theta_1 - \theta_2)\\ &+ [(L_1H_1)^{-1}B_{13} - \frac{C_1}{4}](\theta_1 - \theta_3)\\ &+ [(L_1H_1)^{-1}B_{14} - \frac{C_1}{4}](\theta_1 - \theta_4)\end{aligned}$$

Fig.5 shows the block diagram of uniform heating control system. As shown in the figure, control system consists of enhanced couplings and set point regulators. In the feedback law (16), first term means the average temperature feedback of all measured points, and other terms mean the gradient temperature.

In the recent process control, temperature controller with gradient temperature control (GTC) algorithm proposed in Matsunaga (2005) are utilized for uniform control of heat plate in the manufacturing process. With simple proof, it is confirmed that GTC is one type of the controller proposed in this paper.

4. EXPERIMENTAL RESULTS

4.1 Experimental setup

The two dimensional heat plate is shown in Fig.6 which is simulated the heat plate used in the manufacturing processes. The size of heat plate is $150 \times 150[mm^2]$ with $3[mm]$ thick, and the plate is made of aluminum. Each ceramic heaters are located at distance $50[mm]$ apart. The maximum power of each heater is $100[W]$ and its size is $10 \times 20[mm^2]$. The temperatures are measured with type-K thermocouples screwed on the opposite side of the aluminum plate from the heaters. This heat plate is air-cooled constantly with cooling fans. The environmental temperature was about 30[^{o}C] . The heaters are driven by solid state relay (SSR) with phase control, and sampling rate of controller is 0.1[s].

In experiments, temperature uniformity of two typical layouts as shown Fig.7 will be compared. In layout1 and layout2, heaters are utilized evenly and unevenly as shown in Fig.7.

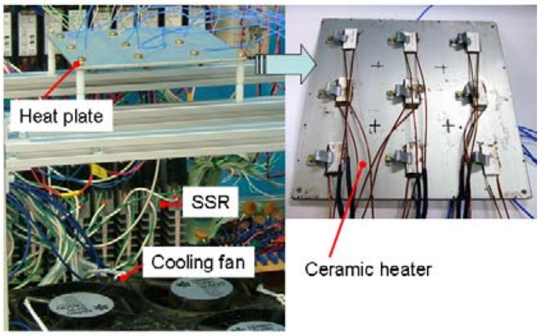


Fig. 6. Experimental system of heat plate

(a)layout1 (b)layout2

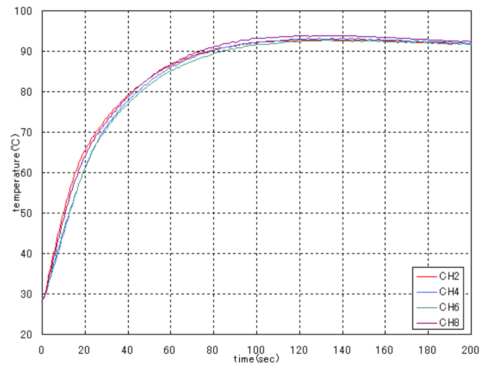
Fig. 7. Typical layout of the heaters

The dynamics of each layout is evaluated in preliminary examination. Fig.8 shows the step response of the heat plate with sequential loop closing by a simple PID controller. The same PID gains are used in each controller. Initial temperature is about 30[^{o}C] and reference temperature is set as 90[^{o}C]. From Fig8(a), it seems that each channel has similar dynamics because the heaters are separated evenly. However, attractive feature is observed that thermal dynamics of CH1 is remarkably fast in Fig.8(b) because of the strong thermal interference from CH2 and CH4.

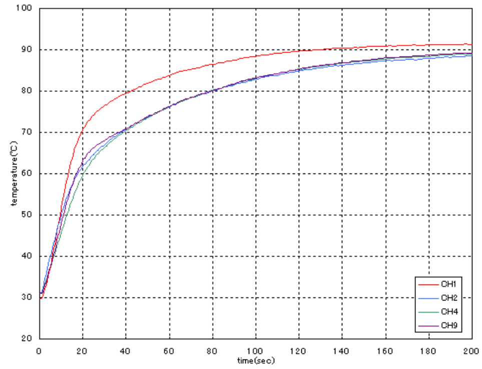
4.2 Design of enhanced coupling controller

In the experiment, 20[W] is applied to all heaters in advance. The temperature of the heater gets to around 70[^{o}C] of equilibrium point. After that, input power of CH2 is increased to 30[W] step from 400 to 2800[s]. Fig.9(a) shows the temperature responses of layout1. From the figure, temperature of other channels are increased by the thermal interference with increasing temperature of CH2. Also, the temperature response of layout2 is shown in Fig.9(b). The equilibrium temperatures are different because of asymmetry layout of the heaters.

Thermal interference β_{ij} are identified from these step response as shown in Table.1. It is notes that thermal interference can be approximated geometrically as $\beta_{ij} = \frac{\lambda A_s}{d_{ij}}$, where d_{ij} is the distance from cell a to b.

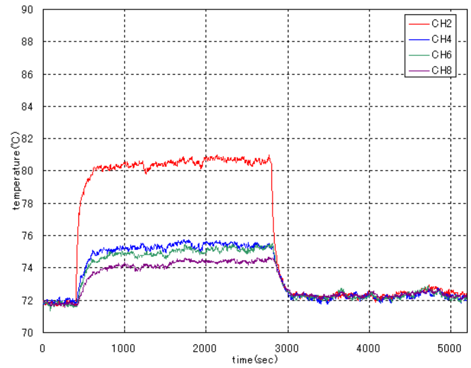


(a)layout1

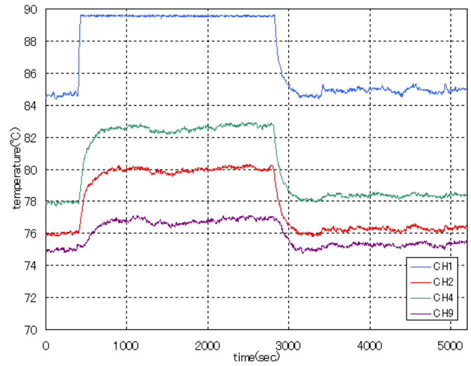


(b)layout2

Fig. 8. Step response with PID control



(a) layout1



(b) layout2

Fig. 9. Step response of the heat plate (open loop)

First, the enhanced coupling controller based on the TDM is constructed using eq.(8). Fig.10 show the step response with setting $K_{pp} = -10$. From the figures, it is summarized

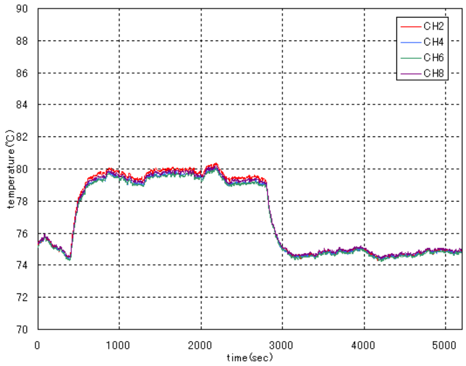
Table 1. Thermal interference β_{ab}

layout1

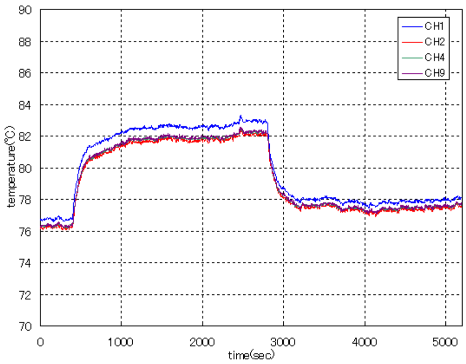
β_{24}	β_{26}	β_{28}	β_{46}	β_{48}	β_{68}
0.57	0.66	0.36	0.43	0.64	0.56

layout2

β_{12}	β_{14}	β_{19}	β_{24}	β_{29}	β_{49}
0.89	0.81	0.20	0.57	0.31	0.33



(a) layout1



(b) layout2

Fig. 10. Step response with coupling feedback

that temperature uniformity is almost achieved. But there is a measurable error in CH1 in Fig.10(b) because the interference from the heater closed by CH1 is large.

4.3 Design of set point regulator

By enhanced coupling controller, the step response of layout1 can be approximated as

$$G_{layout1} = \frac{1.85e^{-5s}}{80s+1} \tag{16}$$

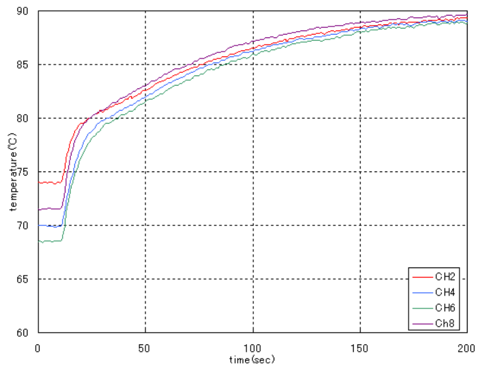
and step response of layout2 is as

$$G_{layout2} = \frac{2.16e^{-10s}}{127s+1} \tag{17}$$

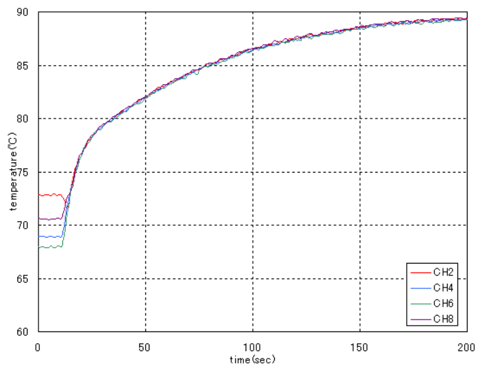
The time constant and dead time of layout1 are changed to 160[%] and 200[%] in layout2, respectively.

Secondly, to regulate the enhanced coupled plant, PID controller C are designed as

$$C = K_p\left(1 + \frac{1}{sT_i} + \frac{sT_d}{1+sT_d/N}\right) \tag{18}$$



(a)traditional method (B=0)



(b)proposed method

Fig. 11. Step response with proposed control (layout1)

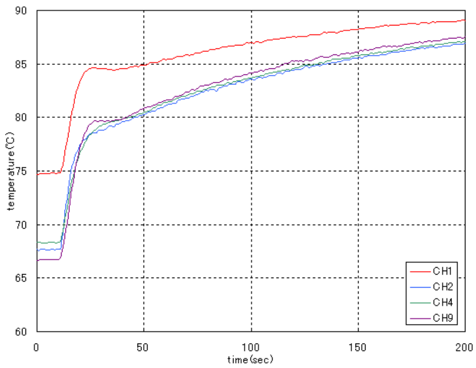
where N gives a limitation of high-frequency gain (Astrom (2005)). The PID parameters can be determined using the CHR method based on the eq.(16) and eq.(17).

Notes that the manipulated variables are saturated when $r - \theta_i$ has been large. During the saturation, the enhanced coupling controller do not work well. Thus, the PID parameters are adjusted to small value not to saturated the manipulated variables in the experiment.

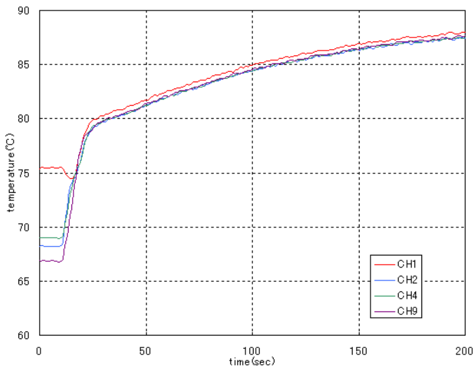
4.4 Evaluation of the uniform heating

Fig.11(a) shows the step response with the traditional PID controller(B=0), and Fig.11(b) shows the step response with the proposed controller. In the experiment, the temperature control is started at t=10[sec] with $\{K_p, T_i, T_d, N\} = \{2.15, 80.0, 6.00, 1\}$. Also, the initial temperature of each channels are different to emphasize on the control effect. In Fig.11(a), each temperature rises with similar dynamics and the settling time of temperature difference becomes long. In order to realize the uniform heating, ad-hoc gain tuning is required additionally.

The step response with uniform temperature control of layout2 is shown in Fig.12. In the experiment, the PID parameters are set as $\{K_p, T_i, T_d, N\} = \{2.15, 127, 16.4, 1\}$. From the figure, although temperature increases in lower speed, it seemed that the proposed control provides good uniformity as well as layout1. Additionally, the settling times to be uniform temperature are compared. Fig.13 demonstrated the maximum temperature difference $max\theta_i - min\theta_j$. We define that settling time T_{settle} is the time it takes before the maximum temperature remains within the

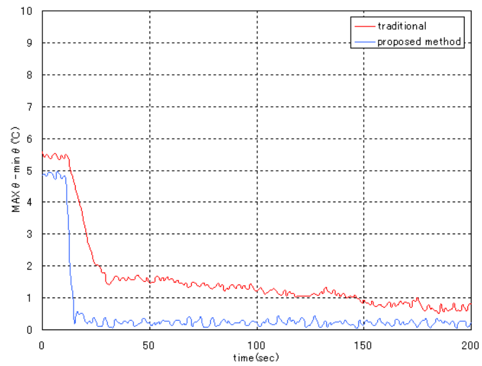


(a)traditional method (B=0)

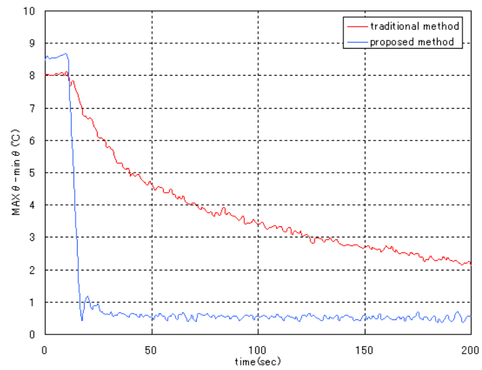


(b)proposed method

Fig. 12. Step response with proposed control (layout2)



(a) layout1



(b) layout2

Fig. 13. Maximum temperature difference

threshold θ_{th}. Although θ_{th} depends on applications, θ_{th} is set as 1 [^{o}C] in this paper.

In layout1, $T_{settle} \approx 140$[sec] with the traditional control, but the settling time is improved to 5 [sec] with proposed controller. The settling time of layout2 is longer than that of layout1, and $T_{settle} \approx 10$[sec] with proposed controller. It is supposed that the CH1 is greatly affected by the heat flows from CH2 and CH4, and hot spot is generated around the area. In general, ad-hoc PID gain tuning to realize uniform responses will be difficult. However, proposed method will be easy to design an uniform temperature controller and it is expected to implement the controller easily in commodity thermal controller.

5. CONCLUSION

In this paper, the feedback controller for uniform heating was designed based on the two dimensional TDM that explicitly represents the thermal interference term β_{ij}. The experimental results for typical layout of the heaters are examined and its effectiveness to uniform temperature control is confirmed. The controller proposed in this paper will be easy to understand for electrical engineers who design the thermal system because the procedure of proposed controller design is similar to one of the heat plate design.

In case that the heaters are located evenly, each cells had similar thermal dynamics and a good uniformity was provided. However, in case that the heaters are located asymmetrically, thermal interference decreased uniformity. According to the increase of K_{pp}, temperature uniformity increases, but the output turns to oscillation in high gain. So, it is concluded that the design of uniform temperature controller considering the dynamics of thermal interference, i.e. distributed lag, will be important issue. Furthermore, in general the TDM will be complex according to the division number of cells. One way to sidestep the difficulty, we believe that the hierarchical design considering dynamics, e.g. the dead time or distributed delay, will be effective. Our future studies are establishing the systematic design considering the characteristics of thermal dynamics.

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