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Invited Paper

Experimental Verification of Slow Mode Based Control Method with Decoupling Compensation for MIMO System

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Abstract. In order to achieve high-quality and high-performance thermal processing, multi-input multi-output temperature control is required. In this paper, the slow-mode based temperature control (SMBC) is proposed with decoupling compensation. The experiments are carried out to verify the SMBC method combined with the decoupling compensation.

1. Introduction

In recent years, thermal processing systems that incorporate temperature control are needed in order to achieve high-quality and high-performance processing. Among the various thermal processing techniques, the PID controller has become the most commonly used controller due to its simplicity and applicability, even for multi-point temperature control systems. In these systems, decoupling compensation and dead time compensation have been combined with the PID controller in order to eliminate their effects [1-6]. Moreover, the feedforward compensation method, the data-driven tuning method and the gradient temperature control method are proposed in [7-9].

In response to the demand for proper transient responses and in order to provide more closely controlled temperatures, a novel multi-point temperature control method based on the slow response mode has been proposed in [10]. In the proposed method, the temperature differences and transient characteristics of all points can be controlled by making the output of the fast modes follow the output of the slow mode. In this paper, the Slow-Mode Based Control (SMBC) combined with decoupling compensation is investigated in the multiple-input multiple-output (MIMO) system with dead time by experiments.

2. Slow-Mode Based Control

2.1 Configuration of SMBC

In this section, the configuration of the proposed slow-mode-based control (SMBC) system is described. To simplify the multi-input and multi-output (MIMO) delay system, the controlled object is defined as a two-input two-output system. The block diagram of SMBC is presented in Fig. 1.

In the figure r and y indicate the reference and output temperature, respectively. The subscripts 1 and 2 mean the slow mode and fast mode, respectively. The gain, time constant and dead time of the plant are expressed by *K*, *T* and *L*. The proposed structure is divided into five blocks.

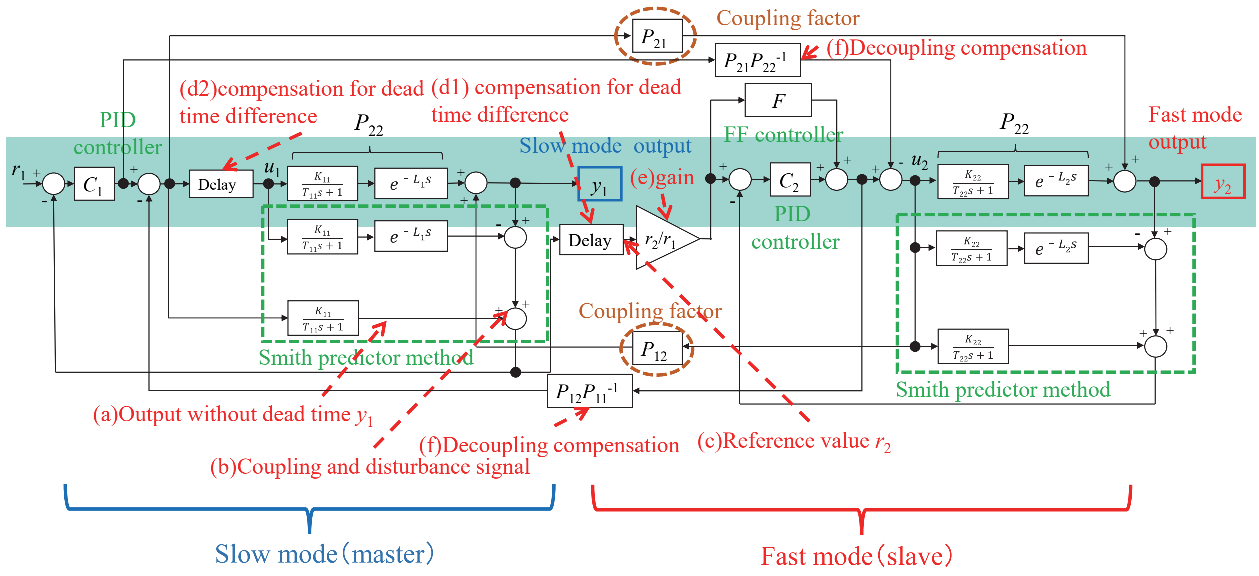


Fig. 1. Block diagram of SMBC system

A. Structure in which the fast-mode outputs are based on the slow-mode output

In order to make the temperature difference between two points close to zero, the output of the slow response mode is used as the reference value for the fast response modes.

B. Structure for obtaining a fast-mode reference value

In the proposed control structure, the Smith predictor method is used for both dead time compensation and reference generation, as shown in Fig. 1. The model output without dead time y_1, which is indicated by (a), is used as the reference value r_2 (*c*) for the fast mode. This structure allows avoidance of a further delay of the fast mode response due to the delay of the slow-mode output.

Moreover, adding a signal that includes a disturbance, coupling, and modeling error (b) to the steady-state error of the fast mode output (a) can be avoided without identifying or estimating these signals.

C. Structure of feedforward compensation for the fast-mode reference value

The feedforward path is added in order to compensate for the dynamic delay of the fast-mode system, so that the fast-mode output follows the slow-mode output without delay. This compensation makes the temperature differences between slow mode and fast mode extremely small.

D. Structure of compensation for dead time difference between the fast mode and the slow mode

There is a difference in dead time between the fast mode and the slow mode. As a result, a temperature difference remains in the outputs of both modes. In order to avoid this problem, when the dead time of the slow mode (L_1) is larger than that of the fast mode (L_2), the reference value of the fast mode is delayed by the difference (L_1- L_2) (as indicated by (d_1) in Fig. 1). This compensation causes both outputs to have the same dead time, i.e., L_1. On the other hand, when L_1 is smaller than L_2, the delay of the slow mode is included as (L_2- L_1) (as indicated by (d_2) in Fig. 1), so that both outputs have the same dead time, i.e., L_2. As a result, the temperature difference between the two modes can be minimized.

E. Structure enabling control of the output ratio of two modes

In the proposed slow-mode-based control method, the output ratio can be controlled even when the reference temperatures at multiple points are different. The gain block (r_2/ r_1) (as indicated by (e) in Fig. 1), which is located after the reference (r_2), corresponds to this part. The fast-mode output follows different references from the slow-mode reference while maintaining its ratio constant. As a result, the settling time and ratio of each output's trajectory can be precisely coincided in each mode.

2.2 Design of decoupling compensation design

In actual MIMO temperature control system, the system is affected by strong coupling effect. Therefore the decoupling compensator is requisite to reduce the coupling influence between the slow mode and the fast mode. The block diagram of the decoupling compensator is shown in Fig. 2, where the C_{21} and C_{12} is the decoupling compensator between the two modes and can be calculated as Equs. (1) and (2),respectively, the P_{21} and P_{12} is the coupling effectiveness between the two modes.

$$C_{12} = P_{12} P_{11}^{-1} \tag{1}$$

$$C_{21} = P_{21} P_{22}^{-1} \tag{2}$$

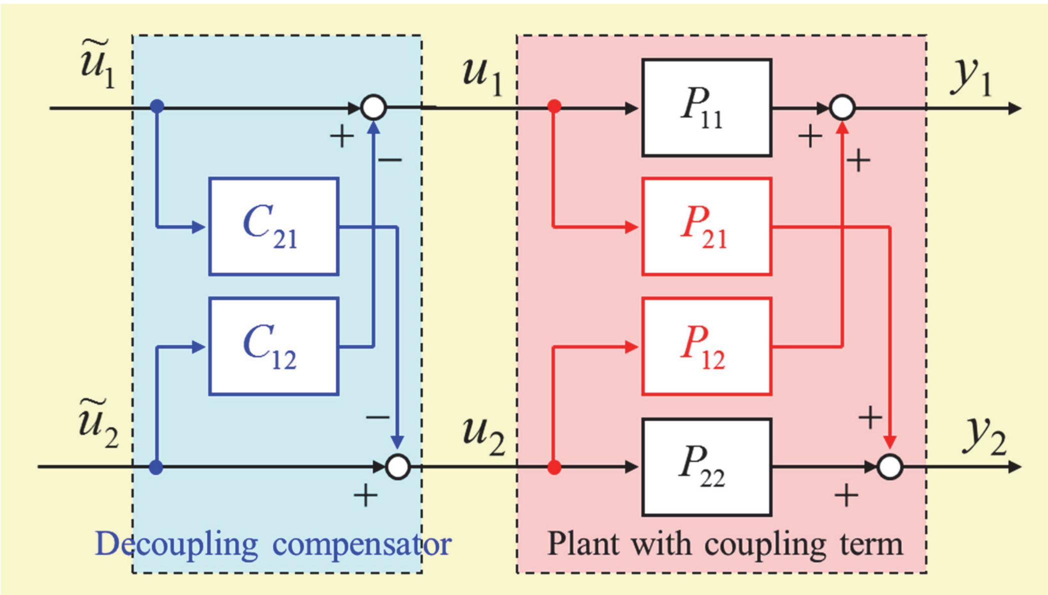


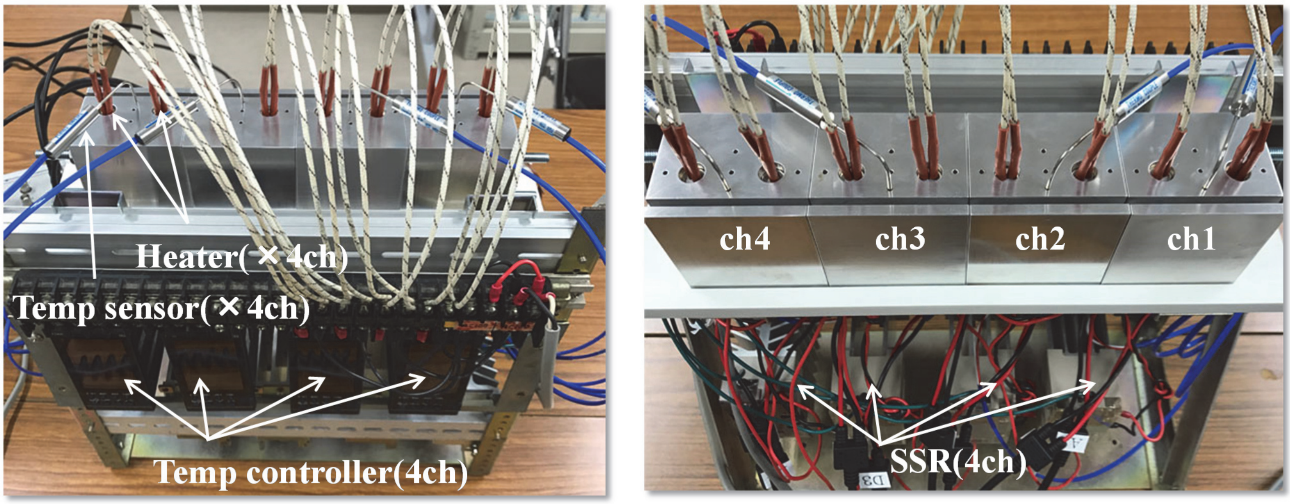
Fig. 2 Decoupling block diagram

The designs of the decoupling compensator can be considered as three types: 1) The compensator considering full dynamics of the plant and dead time difference. 2) The compensator considering the transient compensation with high frequency gain and dead time difference. 3) The compensator considering only the high frequency gain of the coupling effect. In this design, the simplest compensator to compensate the coupling effect is conducted.

3. Experimental Results

3.1 Experimental Platform

Fig. 3 shows the experimental setup for the MIMO heating system with strong coupling effect, that equips DSP as the temperature controller. The system has four coupling channels, each channel has independent heaters and temperature sensor. The temperature can be controlled through the duty ratio of PWM.



Front view Rear view

Fig. 3 Experimental setup

In the experiments, the two channels: Ch1 and Ch3 are used as control object to apply the SMBC control method, and the system dynamics is identified as Eq. (3).

$$P_{MIMO} = \begin{bmatrix} P_{11} & P_{13} \\ P_{31} & P_{33} \end{bmatrix} = \begin{bmatrix} \dfrac{4.52}{1211s+1}e^{-25s} & \dfrac{1.91}{5848s+1}e^{-125s} \\ \dfrac{1.67}{3984s+1}e^{-150s} & \dfrac{4.34}{1639s+1}e^{-30s} \end{bmatrix} \quad (3)$$

According to the identified plant transfer function, Ch3 is the slow response mode and Ch1 is the fast response mode. So the experiment is carried out by using Ch3 output as the fast mode reference and Ch1 output follows the output temperature of Ch3.

The PI controllers for Ch1 and Ch3 are designed as Eqs. (4) and (5), respectively.

$$C_1 = \frac{1211s+1}{178s} \quad (4)$$

$$C_3 = \frac{1639s+1}{178s} \quad (5)$$

For the decoupling compensators, the high frequency gains are divided as C_{13}=0.0875 and C_{31}=0.158, respectively.

3.2 Experimental results

In order to realize the SMBC structure, the experiments are divided into two steps. Step1: SMBC system with the Smith predictor compensation. Step2: SMBC system with the Smith and feedforward compensations. Step 3: SMBC system with Smith, feedforward and decoupling compensations.

The step signal was applied to the slow-mode reference(Ch3). Experimental results of the first two steps are shown in Figs.4 and 5, respectively. For the feedforward compensation, the gain 0.5 was multiplied due to the noise amplification. The results of the step 3 combined with the decoupling compensation are shown in Fig. 6.

In order to evaluate the proposed SMBC method with decoupling compensation, a conventional PI with decoupling compensation method was also carried out. Experimental result is shown in Fig. 7.

From these results, compared with the conventional control, the SMBC with smith compensation has no overshoot. The maximum errors of the proposed SMBC and the conventional PI with decoupling control were 0.30 and 0.34 degree, respectively. It can be slightly improved by adding the feedforward controller. After adding the decoupling compensator, the temperature becomes smoother with reducing coupling effects.

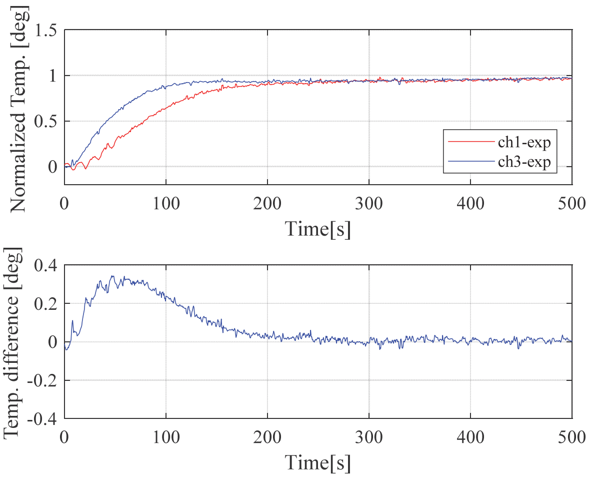


Fig. 4 SMBC with Smith predictor compensation

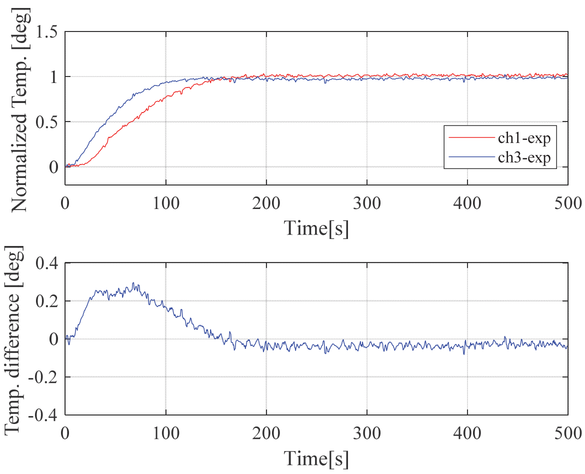


Fig.5 SMBC with Smith and feedforward compensations

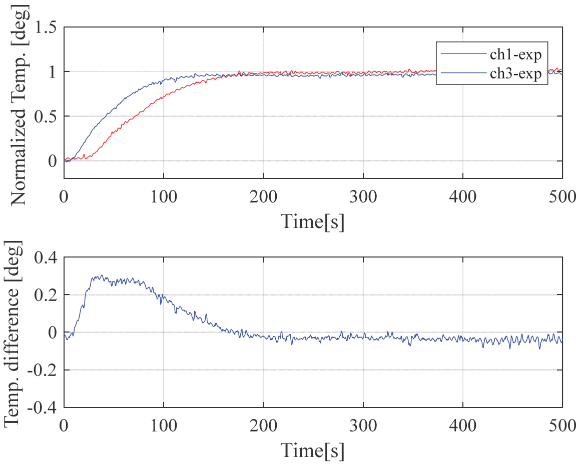


Fig. 6 SMBC with Smith, feedforward and decoupling compensations

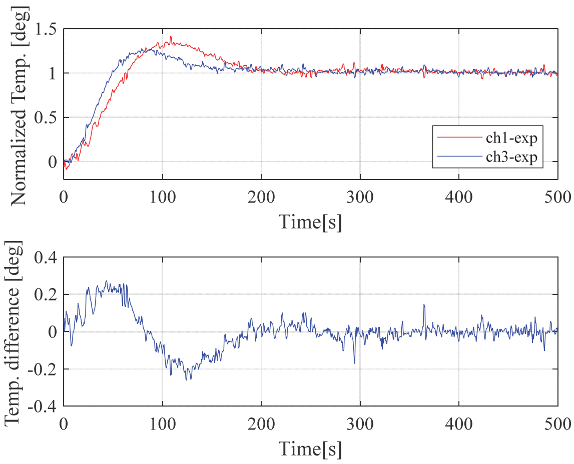


Fig. 7 Conventional PI and decoupling control

4. Conclusion

In this paper, the slow-response mode based control with decoupling compensation for the MIMO delay system has been proposed. The experiment has been carried out with three steps to show the effectiveness of the SMBC control method with decoupling compensation, compared with the conventional PI with decoupling compensation method. Future work will be focused on the improvement of the feedforward gain.

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