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Slow Response Mode-Based Multi-point Temperature Control

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Abstract. Thermal processing systems that incorporate temperature control are needed in order to achieve high-quality and high-performance processing. In the present paper, 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 is proposed. In the proposed method, the temperature differences and transient characteristics of all points can be controlled by making the output of other modes follow the output of the slow mode. The effectiveness of the proposed method is evaluated through simulations.

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 [1,2,3,4,5]. Moreover, the feedforward compensation method, the data-driven tuning method and the gradient temperature control method are proposed in [6,7,8,9,10,11]. The main purpose of these compensation methods is to improve transient response and to reduce the temperature differences between the multiple points to zero. However, the PID controller with these compensation methods cannot consider these requirements simultaneously.

In the present paper, 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 is proposed. In the proposed method, the temperature differences and transient characteristics of all points can be controlled by making the output of the other modes follow the output of the slow mode. The effectiveness of the proposed method is evaluated through simulations.

2. Difficulties in Multi-point Temperature Control

From the viewpoint of practical application of multi-point temperatures control, fine-tuned PID controllers with decoupling and dead time compensations are utilized. The Ziegler-Nichols' ultimate gain method and the CHR method are representative heuristic methods based on experimental data [1,2]. These methods attempt to make the actual temperatures follow the reference values while minimizing the temperature differences between multiple points. However, in many cases, the following difficulties still exist. 1) The PID controller must be designed considering the effect of the dead time of the controlled objects. 2) Although the temperature difference is somehow decreased due to this consideration, a significant improvement in transient response cannot be expected. 3) Improving the transient response causes the disturbance response to deteriorate. 4) Finally, when the reference values of multiple points are different, it is difficult to control the individual settling times with the same temperature ratio.

3. Configuration of SMBC System

In this section, we describe the configuration of the proposed slow-mode-based control (SMBC) system. Fig. 1 shows a block diagram of the proposed SMBC system. For simplicity, the controlled object is defined as a two-input two-output system. In Fig. 1, 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.

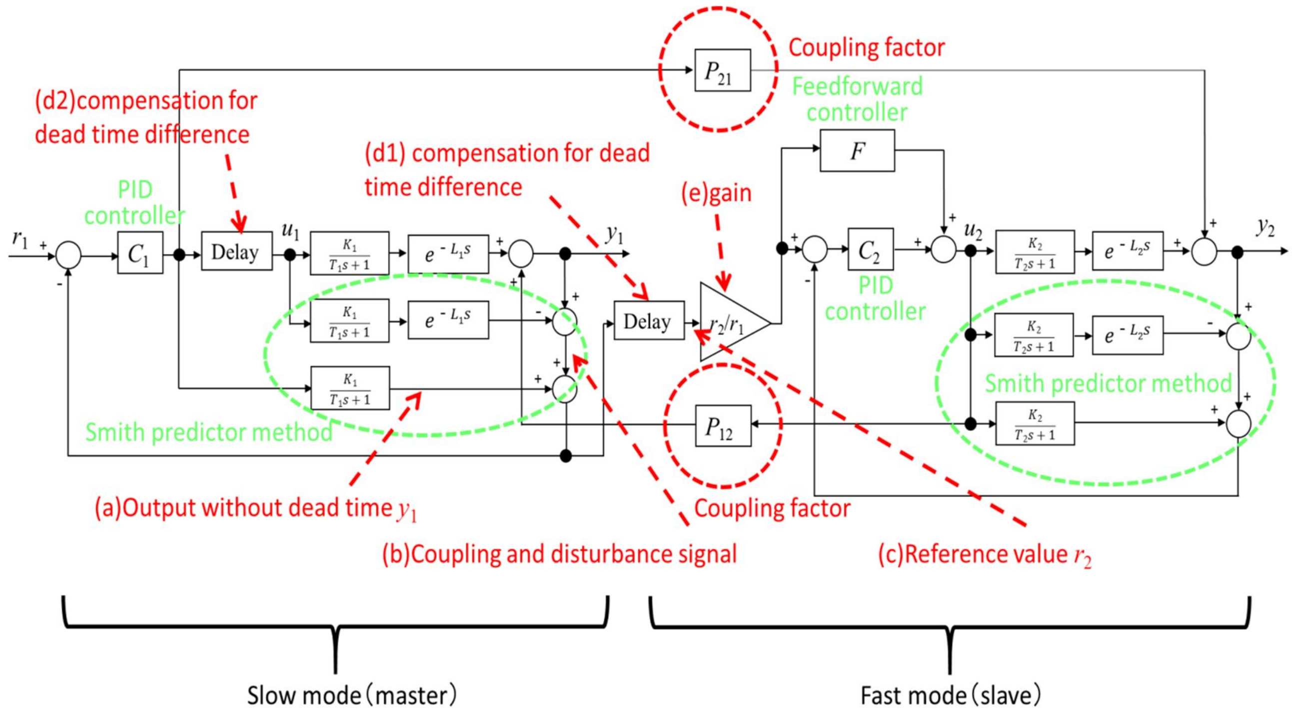

Fig. 1. Block diagram of SMBC for two-input two-output system

3.1 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.

3.2 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.

3.3 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.

3.4 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 (d1) 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 (d2) 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.

3.5 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 (r2/ r1) (as indicated by (e) in Fig. 1), which is located after the reference (r2), 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.

4. Simulation Results

In simulations of a multipoint temperature system, the control object G_p is defined with two-input and two-output vectors as follows:

$$G_p = \begin{bmatrix} \frac{500}{200s+1}e^{-3s} & \frac{300}{2000s+1}e^{-5s} \\ \frac{400}{1000s+1}e^{-4s} & \frac{600}{150s+1}e^{-2.5s} \end{bmatrix} \tag{1}$$

Each factor is represented by a first-order lag system with dead time. Comparing the time constants of diagonal factors in (1), the first-input/first-output system, i.e., the factor (1,1), can be defined as the slow mode, whereas the factor (2,2) can be defined as the fast mode.

Figs. 2 (a) and (b) show the set-point tracking results for the control inputs and temperature outputs for the system obtained using the standard PID controller designed by the Ziegler-Nichols method [1]. Fig. 2 (c) shows the temperature difference, (y_1- y_2), and the mean temperature, (y_1+y_2)/2. As shown in Fig. 2 (c), the overshoot of the mean temperature reaches 93.3 %, and the maximum temperature difference becomes 51.2 deg.

Fig. 3 shows the time response for the system which includes all structures described in Section 3. Fig. 3 indicates that the two outputs respond with no time difference and that the fast-mode output can follow the slow-mode output. Due to the coupling effect, a small temperature difference is observed. However, the overshoot of the mean temperature and the maximum temperature difference are improved to 18.9 % and 11.1 deg, respectively.

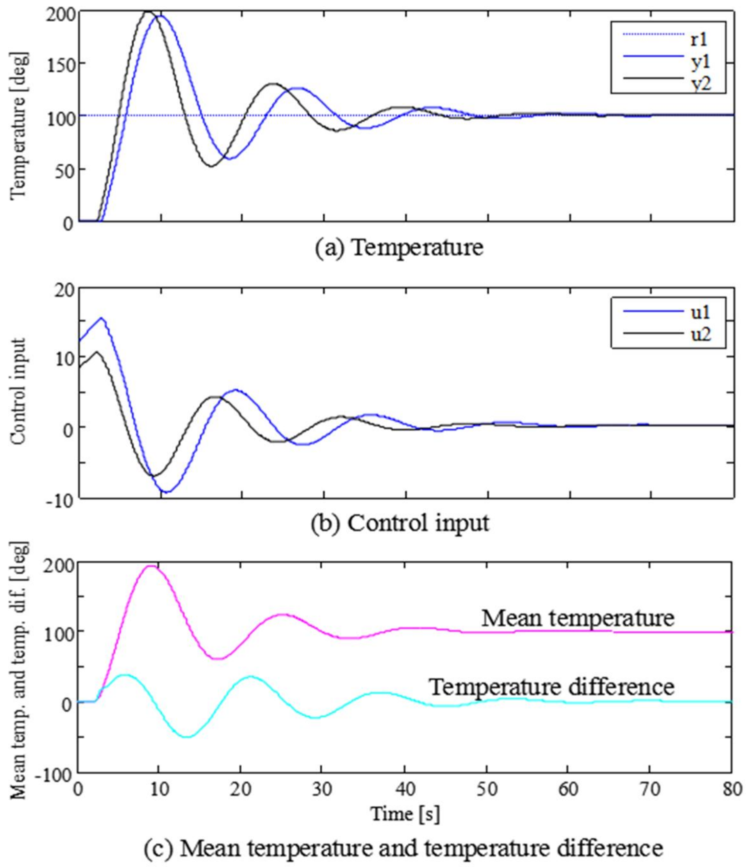

Fig. 2. Set point tracking results for PID control

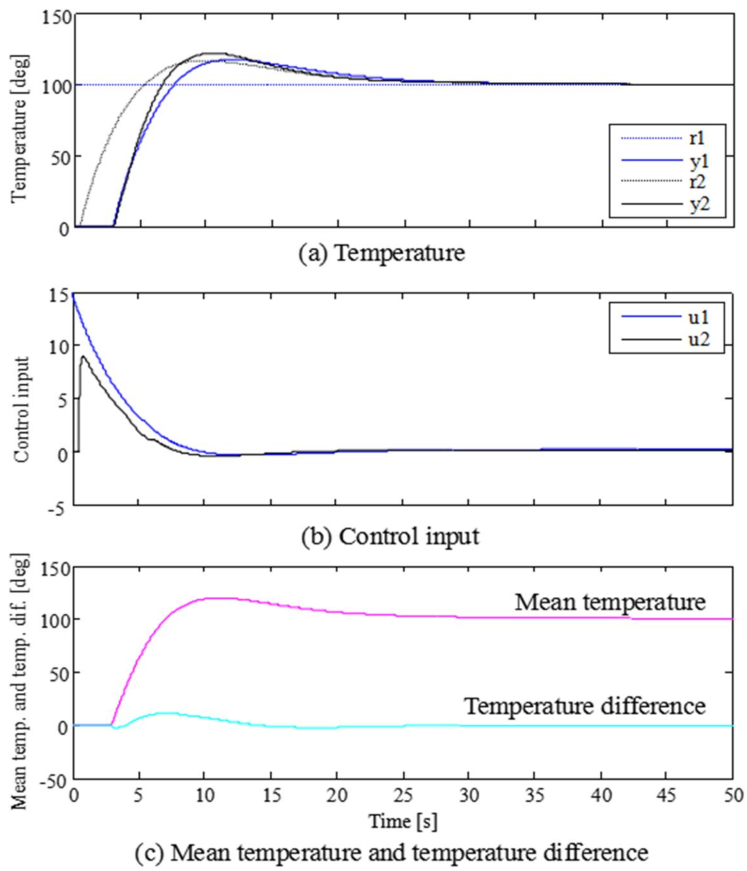

Fig. 3. Set point tracking results for combined SMBC system

5. Conclusion

In the present paper, a novel multi-point temperature control method based on the slow response mode was proposed. The main purposes of the proposed method are to ensure proper transient responses and to provide more closely controlled temperatures. In the proposed method, the temperature differences and transient characteristics of all points can be controlled by making the outputs of the other modes follow the output of the slow mode. The effectiveness of the proposed method was evaluated though simulations comparing the proposed slow-mode-based control with Ziegler-Nichols-based PID control for the case of a two-input two-output plant. In the future, we intend to analyze the disturbance characteristics of the proposed method and evaluate of robustness of the proposed method against modeling errors.

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