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CONTROLLER DESIGN TO DIMINISH OSCILLATION AND STEADY STATE ERROR IN WATER TEMPERATURE SYSTEMS WITH DRIVE DELAY

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ABSTRACT

Systematic design of a controller for a water temperature system was considered, with the intention of devising an accurate control experiment. The results of an experiment using a water temperature system based on the pole placement regulator showed water temperature oscillation and steady state error. This paper proposed a method for eliminating both the oscillation and the steady state error. The oscillation was eliminated by a drive delay compensation technique, in which a future state value of the system was predicted through a real time computer simulation. The steady state error was eliminated by an steady state error correction technique, in which an actual steady state heatrate in the system model was replaced by an imaginary heatrate. By combining these two techniques, we obtained an experimental result for water temperature control of 0.01 (°C) accuracy. Furthermore, the proposed method was evaluated relatively by comparing the experimental results using several other methods and proved to be the most accurate and convenient control method for the delay system.

1. INTRODUCTION

Temperature control of tanked water or any other liquid is an important problem in industries such as warm water supply systems, heating and cooling systems of industrial products, chemical plants, etc. There has been much research about temperature control aimed at devising an accurate control experiment: water temperature control by using an adaptive observer [1]; ocean thermal energy conversion by using a pole placement regulator for an augmented system [2]; boiler control in a thermal power plant by using an optimal regulator [3]; and temperature control of a chemical pilot plant by an adaptive regulator [4]. In seeking to obtain accurate control performance, we encounter many problems, and of these, the delay time in a given system is one of the most enigmatic. The Smith method [5],[6] is a well-known compensation method for a system with a delay time in which the system is analyzed in a frequency domain. Watanabe and Ito [7] proposed the compensation method for delay time by using prediction by an observer, and Shimemura, Uchida and Kubo [8] investigated the method of compensating for delay time by an optimal regulator in a state space representation. Research concerning a control system with delay time is summarized in a survey paper [9]. However, the proposed methods of compensation for a delay system were rarely evaluated by experimental means.

This paper describes a controller design for a water temperature system, with the intention of devising an accurate control experiment. The results of an experiment for a water temperature system based on the pole placement regulator showed water temperature oscillation and steady state error. We proposed a method for eliminating both the oscillation and the steady state error. The oscillation phenomenon was found to be caused by a drive delay in the heater.

The oscillation was eliminated by using the drive delay compensation control method in which a future state value of the system was predicted through a real time simulation. The steady state error was eliminated by using the correction method, in which the steady state heatrate was replaced by the imaginary heatrate as estimated in real time. By combining these two control techniques, we obtained a high-accuracy experimental result for water temperature system control. Furthermore, we compared experimental results by several methods: the PID controller, the servo system of the first order, and the first order servo system compensated for the drive delay system. Among those techniques, the proposed method showed the most accurate control performance.

2. SYSTEMATIC CONTROLLER DESIGN FOR WATER TEMPERATURE SYSTEM

2. 1 Equipment of Water Temperature System

The control objective in this study is to regulate heater output so that the water temperatures in two tanks respectively pursue the desired values. The equipment of a tanked water system, shown in Fig. 1, consists of two water tanks of control object, electric heaters of actuators with triac circuits, and thermometers of detectors. Water in each tank is heated by its own electric heater and cooled by water from a cooling tank. The tanked water is mixed by a motor to achieve uniform temperature distribution of the tanked water throughout the experiment period.

2.2 Systematic Controller Design

Since a digital controller designed according to modern theory is required to grasp the characteristics of the controlled object precisely, the structure of the controller usually becomes more complex than that of the PID controller. If we express the controller as a mirror image of the controlled equipment, we can classify the structure into three parts: the restoration characteristics of detector part, the control theory part, and the restoration characteristics of actuator part [10]. The procedure for designing the digital controller is summarized in the following five steps: i) statement of control

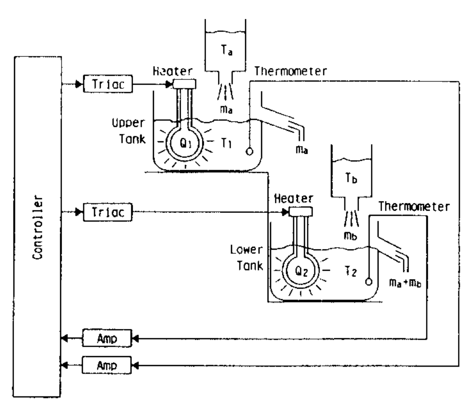

Figure 1 Water temperature system equipment: upper and lower water tanks, heaters, and thermometers.

objective, ii) modelling of controlled object, iii) application of control theory, iv) characterization of detector and actuator, v) construction of controller.

Modelling of controlled object

The dynamic equation is derived by the heat balance law. Letting the heat change of the tanked water be equal to the inflow heatrate minus the outflow heatrate for a short time interval and taking the infinite minimization of the time interval, we obtain the mathematical model for the controlled object as

$$\dot{T}_1 = \{Q_1 - m_a(T_1 - T_a)\}/W_1,$$
$$\dot{T}_2 = \{Q_2 - m_a(T_2 - T_1) - m_b(T_2 - T_b)\}/W_2 \qquad (1)$$

where subscript 1 refers to the upper tank and subscript 2 to the lower tank, T_1 and T_2 (°C) the water temperatures in the respective tanks, W_1 and W_2 (cm^3) the mass of the tanks, Q_1 and Q_2 (cal/s) the output heatrates of the heaters, the specific heat of the water is 1 (cal/°Cg) and the density of the water is 1 (g/cm^3). The cooling water of the temperature T_a (°C) of flow rate m_a (cm^3/s) flows into the upper tank and the cooling water of T_b (°C), m_b (cm^3/s) flows into the lower tank. For the equipment, those values are as follows: $W_1 = 2,600$ (cm^3), $W_2 = 2,100$ (cm^3), $m_a = 8.5$ (cm^3/s), $m_b = 6$ (cm^3/s).

Using the state vector $X = [X_1, X_2]^T = [T_1 - T_1^*, T_2 - T_2^*]^T$, and the manipulated vector $U = [U_1, U_2]^T = [Q_1 - Q_1^*, Q_2 - Q_2^*]^T$, we obtain the state space representation for the equation (1) as

$$\dot{X} = AX + BU \qquad (2)$$

where

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} -m_a/W_1 & 0 \\ m_a/W_1 & -(m_a + m_b)/W_2 \end{bmatrix},$$
$$B = \begin{bmatrix} 1/W_1 & 0 \\ 0 & 1/W_2 \end{bmatrix}$$

and $Q_1^* = m_a(T_1^* - T_a)$, $Q_2^* = m_a(T_2^* - T_1^*) + m_b(T_2^* - T_b)$, T_1^* and T_2^* are the desired value of the respective tanked water. Discretizing the equation (2) with a sampling interval h, we obtain the transition equation as

$$X(k+1) = \Phi X(k) + DU(k). \qquad (3)$$

The matrices in (3) are expressed as

$$\Phi = \begin{bmatrix} \phi_{11} & 0 \\ \phi_{21} & \phi_{22} \end{bmatrix}, \quad D = \begin{bmatrix} d_{11} & 0 \\ d_{21} & d_{22} \end{bmatrix}$$

where $\phi_{11} = \exp(a_{11}h)$, $\phi_{21} = a_{21}\{\exp(a_{11}h) - \exp(a_{22}h)\}/(a_{11} - a_{22})$, $\phi_{22} = \exp(a_{22}h)$, $d_{11} = 1/m_a\{1 - \exp(a_{11}h)\}$, $d_{21} = a_{21}/m_a(a_{11} - a_{22})\{1 - \exp(a_{11}/h)\} - W_2 a_{21}/W_1(m_a + m_b)(a_{11} - a_{22})\{1 - \exp(a_{22}h)\}$, $d_{22} = 1/(m_a + m_b)\{1 - \exp(a_{22}h)\}$.

Control theory

We adopt the pole placement regulator to regulate the tanked water temperatures. The manipulated vector is obtained as

$$U(k) = KX(k). \qquad (4)$$

The feedback gain K is calculated so that the poles of the closed loop matrix $(\Phi + DK)$ coincide with given values λ_1 and λ_2, respectively. If the values of the manipulated vector calculated by (4) exceed the maximum outputs of the respective heaters, these values are set at the maximum values. To improve the quick transient response, we adopt the maximum heater output until one of the water temperatures approaches the range of 0.1 (°C).

Characterization of detector and actuator

The restoration characteristic of the detector is defined as an inverse function of the characteristic of detector, and determined by using the least squares method through the experimental check. The restoration characteristics of the thermometers are expressed as

$$T_1 = 21.1 + 4.41V + 3.21 \times 10^{-2}(V)^2 + 1.15 \times 10^{-2}(V)^3,$$
$$T_2 = 13.8 + 6.07V + 2.85 \times 10^{-2}(V)^2 + 3.37 \times 10^{-2}(V)^3. \quad (5)$$

The restoration characteristics of the heater of actuator are also determined as

$$\begin{aligned} V_1 = 5.08 &- 1.05 \times 10^{-1}U_1 - 3.27 \times 10^{-3}(U_1)^2 \\ &+ 3.58 \times 10^{-4}(U_1)^3 - 1.17 \times 10^{-5}(U_1)^4 \\ &+ 1.91 \times 10^{-7}(U_1)^5 - 1.76 \times 10^{-9}(U_1)^6 \\ &+ 9.16 \times 10^{-12}(U_1)^7 - 2.53 \times 10^{-14}(U_1)^8 \\ &+ 2.87 \times 10^{-17}(U_1)^9, \\ V_2 = 5.43 &- 1.21U_2 + 1.69 \times 10^{-1}(U_2)^2 - 1.32 \times 10^{-2}(U_2)^3 \\ &+ 5.44 \times 10^{-4}(U_2)^4 - 1.22 \times 10^{-5}(U_2)^5 \\ &+ 1.38 \times 10^{-7}(U_2)^6 - 6.25 \times 10^{-10}(U_2)^7 \qquad (6) \end{aligned}$$

where V_1 and V_2 are the input voltages to the triac circuits.

Construction of controller

Equations (5), (4), (6) are programmed in sequentially in a personal computer equipped with A/D (analogue-to-digital) converters and D/A converters, which completes the controller.

2. 3 Experimental Result by using a Controller of the Pole Placement Regulator

By using the controller based on the pole placement regulator, we performed an experiment of the water temperature control. The conditions for the experiment were as follows: the initial water temperatures $T_1 = T_2 = 10.3$ (°C), the desired water temperatures $T_1^* = 20$ (°C) and $T_2^* = 18$ (°C), the cooling water temperatures $T_a = T_b = 10.3$ (°C), the maximum outputs of the heaters 186.3 (cal/s) and 46.7 (cal/s), the sampling interval $h = 1$ (s), the values of the poles $\lambda_1 = 0.90$ and $\lambda_2 = 0.91$.

Figure 2 shows the experimental result for the upper tank and the lower tank respectively. It illustrates the water temperature $T(k)$ and the heatrate $Q(k)$ of the heater as

$$Q(k) = U(k) + Q^* \qquad (7)$$

where $Q(k) = [Q_1(k), Q_2(k)]^T$, $Q^* = [Q_1^*, Q_2^*]^T$. We can find some oscillations and slight steady state errors around the desired values. For the upper tank, the oscillation had an amplitude of 0.4 (°C) with period 65 (s), and the steady state error was about 0.1 (°C). For the lower tank, the amplitude was 0.3 (°C), the period 110 (s), the steady state error about 0.05 (°C).

3. ELIMINATION OF OSCILLATION

3. 1 Cause of Oscillation

A cause of the oscillation of the water temperature control was examined through a simulation test. Instead of (3), the controlled object was assumed to be modelled by a system with drive delay as

$$\begin{aligned} X(k+1) &= \Phi X(k) + DZ^{-1}U(k) \\ &= \Phi X(k) + D_1U_1(k - L_1) + D_2U_2(k - L_2) \qquad (8) \end{aligned}$$

where L_1 and L_2 (s) are the delay times for respective tanks, $D = [D_1, D_2]$, and Z^{-1} is the delay matrix

$$Z^{-1} = \begin{bmatrix} z^{-L_1} & 0 \\ 0 & z^{-L_2} \end{bmatrix}.$$

In the simulation study, the system (8) was controlled by the manipulated vector (3) of the pole placement regulator. Out of many values of the delay times, the system with L_1 of 15 (s) and L_2 of 25 (s) showed a similar oscillation to that of the previous experimental result (see Fig. 3). The oscillation of the simulation test had an amplitude of 0.5 (°C) with period 60 (s) for the upper tank and a amplitude of 0.3 (°C) with period 110 (s) for the lower tank. We then concluded that the oscillation in the experimental result was caused mainly by the drive delays in the system.

3. 2 Compensation for Drive Delay by using Real Time Simulation

We now consider compensation for drive delay of the water temperature system expressed by (8). The compensated manipulated vector is given by

$$\bar{U}(k) = ZK\hat{X}(k) = \begin{bmatrix} K_1\hat{X}(k+L_1) \\ K_2\hat{X}(k+L_2) \end{bmatrix} \quad (9)$$

where $\hat{X}(k+L_1)$ and $\hat{X}(k+L_2)$ are the prediction of future states $X(k+L_1)$ and $X(k+L_2)$, and $K = [K_1^T, K_2^T]^T$.

The predicted values are calculated by the real time simulation as

$$\hat{X}(k+j) = \Phi\hat{X}(k+j-1) + D\hat{U}(k+j-1), \quad j = 1, 2, 3, ..., \max(L_1, L_2) \quad (10)$$

where the initial value $\hat{X}(k)$ is set at the current state vector $X(k)$. The imaginary manipulated vector $\hat{U}(k+j-1)$ in the simulation is expressed as

$$\hat{U}(k+j-1) = \begin{bmatrix} \hat{U}_1(k+j-1) \\ \hat{U}_2(k+j-1) \end{bmatrix} \quad (11)$$

where each element is given by

$$\hat{U}_i(k+j-1) = \begin{cases} \bar{U}_i(k+j-1-L_i), & (j \le L_i), \\ K_i\hat{X}(k+j-1), & (j > L_i), \end{cases} \quad i = 1, 2. \quad (12)$$

As the imaginary manipulated vector, we can use the manipulated value already adopted in the actual system, but if not adopted, we must calculate. Applying the compensated manipulated vector (9) to the drive delay system (8), we can prove that the drive delay is recovered and an oscillation around a desired value is eliminated completely[11].

3. 3 Experimental Result by using the Drive Delay Compensation Method

By using the controller based on the drive delay compensation, we performed an experiment in water temperature control. The conditions of the experiment were similar to the previous conditions: the initial water temperatures $T_1 = T_2 = 10$ (°C), the desired water temperatures $T_1^* = 20$ (°C) and $T_2^* = 18$ (°C), the cooling water temperatures 10 (°C), the delay times $L_1 = 15$ (s) and $T_2 = 25$ (s), the sampling interval $h = 1$ (s), the value of the poles $\lambda_1 = 0.90$ and $\lambda_2 = 0.91$.

Figure 4 shows the experimental result. In both tanks water temperature approached the respective desired value without oscillation, and the control performance was improved significantly. When we checked the performance in more detail, we could see slight steady state error; the steady state error of 0.1 (°C) for upper tank and 0.05 (°C) for lower tank. Next we consider the elimination of the steady state error.

4. ELIMINATION OF STEADY STATE ERROR

4. 1 Cause of Steady State Error

We concentrate on the steady state error in the experimental result by using the drive delay compensation control based on the pole placement regulator. To simplify the problem, one tanked water temperature system is considered. Figure 5 shows the experimental result for one tanked water temperature system in an enlarged scale. We can find the steady state error of about 0.02 (°C). Substituting an imaginary

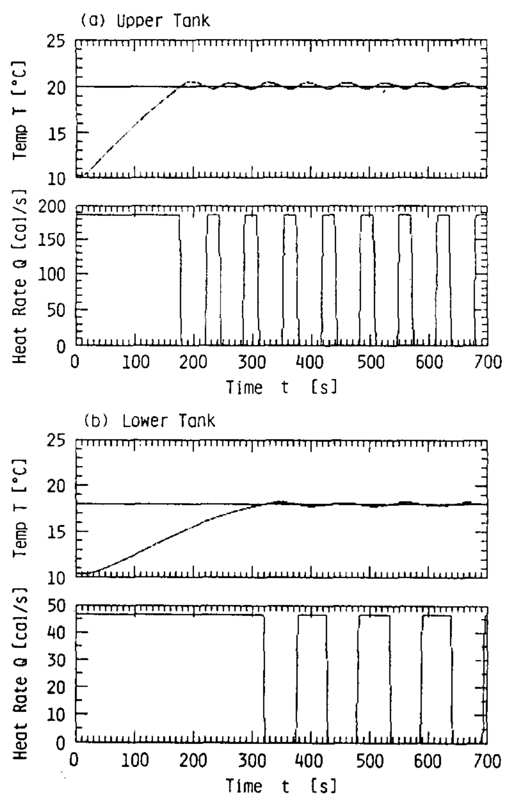

Figure 2 Experimental result for water temperature control by the pole placement method.

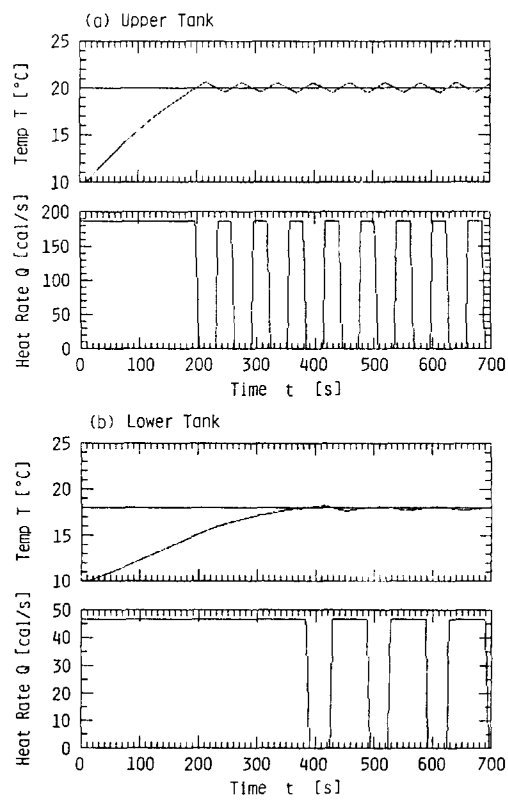

Figure 3 Computer simulation of the experiment: water temperature system with drive delay.

cooling water temperature $\hat{T}_c$ to the actual cooling water temperature T_c in (7), we performed an experimental test by using the proposed method of the drive delay compensation control. For several imaginary cooling water temperatures, a relationship between the steady state errors (mean of the deviations during 400 to 600 (s) after starting point) and the deviations of the imaginary cooling water temperature ($\tilde{T}_c = \hat{T}_c - T_c$) was obtained, as seen in Fig. 6.

The elimination of an steady state error may be achieved by a correction using the deviation of the imaginary cooling water temperature. However, the curve of the deviation is affected by experimental conditions such as a cooling water temperature or temperature of the experimental circumstance etc. Appropriate selection of $\hat{T}_c$ is preferably determined by on-line estimation.

4. 2 Correction of Steady State Error

The steady state error of the tanked water $\tilde{T}(k)$ ($= T(k) - T^*$) is adjusted on line by using the imaginary steady state heatrate. The steady state error $\tilde{T}(k)$ is approximated by the second polynomial of the imaginary cooling water temperature deviation $\tilde{T}_c(k)$ ($= \hat{T}_c(k-1) - T_c$) as

$$\tilde{T}(k) = \alpha_0 + \alpha_1 \tilde{T}_c(k) + \alpha_2(\tilde{T}_c(k))^2 \tag{13}$$

The coefficients of the polynomial are estimated on-line by minimizing the exponential weighted least squares criterion

$$J = \sum_{i=1}^{k} \rho^{k-i}\{\tilde{T}(i) - \alpha_0 - \alpha_1\tilde{T}_c(i) - \alpha_2(\tilde{T}_c(i))^2\}^2. \tag{14}$$

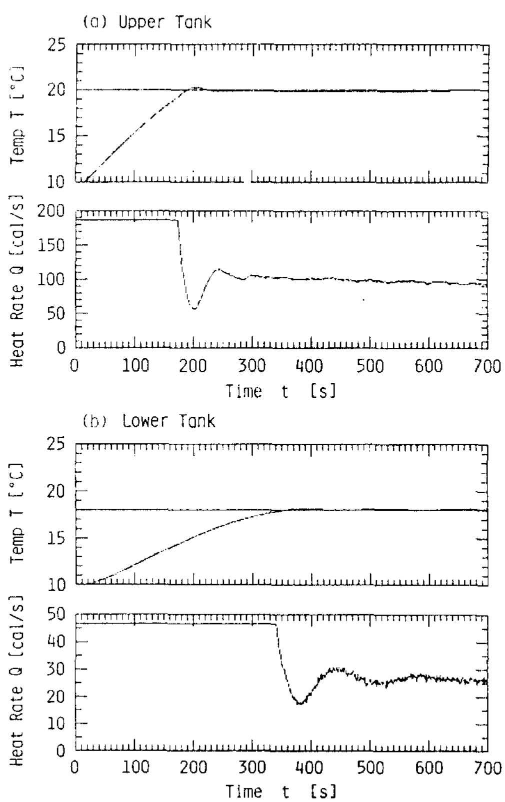

Figure 4 Experimental result for water temperature control by the compensation method for drive delay.

The recursive algorithm derived from the criterion can be expressed as [12]

$$\begin{aligned} G(k) &= C(k-1)\omega(k)/\{\rho + \omega(k)^T C(k-1)\omega(k)\}^{-1}, \\ \hat{\theta}(k) &= \hat{\theta}(k-1) + G(k)\{\tilde{T}(k) - \omega(k)^T\hat{\theta}(k-1)\}, \\ C(k) &= \{1 - G(k)\omega(k)^T\}C(k-1)/\rho \end{aligned} \tag{15}$$

where the vector $\hat{\theta}(k) = [\hat{\alpha}_0(k), \hat{\alpha}_1(k), \hat{\alpha}_2(k)]$, $\omega(k) = [1, \tilde{T}_c(k), (\tilde{T}_c(k))^2]^T$, and the value of the index ρ is chosen appropriately within a range [0, 1] by the designer. At any instance during the control interval, the second polynomial is solved under the condition of being zero of the right hand side in the equation (13). The appropriate imaginary cooling temperature which adjusts the steady state error is

$$\begin{aligned} \hat{T}_c &= T_c + \tilde{T}_c(k) \\ &= T_c - \{\hat{\alpha}_1(k) + \sqrt{(\hat{\alpha}_1(k))^2 - 4\hat{\alpha}_0(k)\hat{\alpha}_2(k)}\}/2\hat{\alpha}_2(k). \end{aligned} \tag{16}$$

The heatrate $Q(k)$ of the heater corrected by the imaginary heatrate $\hat{Q}_c(k)$ can be obtained as

$$Q(k) = \bar{U}(k) + \hat{Q}_c(k) = F\hat{X}(k+L) + m(T^* - \hat{T}_c(k)) \tag{17}$$

where $\bar{U}(k)$ is the manipulated variable obtained by the drive delay compensation control method proposed in the previous section.

4. 3 Experimental Result by Combinational use of Drive Delay Compensation and Steady State Error Correction

By using the controller based on the drive delay compensation and the steady state error correction, we performed an experiment to control water temperature in one tank. The conditions of the experiment were as follows: the initial water temperature $T = 12$ (°C), the desired water temperature $T^* = 20$ (°C), the cooling water temperature $T_c = 12$ (°C), the delay time in the compensation algorithm $L = 8$ (s), the sampling interval $h = 0.4$ (s), the value of the pole in the regulator $\lambda = 0.95$. To improve the transient response the maximum

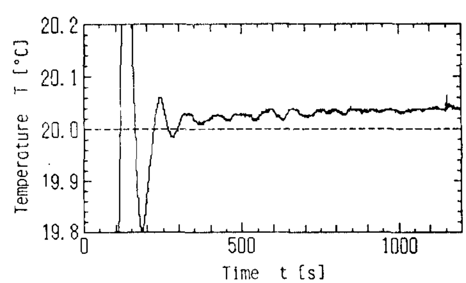

Figure 5 Experimental result for water temperature control by the compensation method for drive delay (enlarged scale).

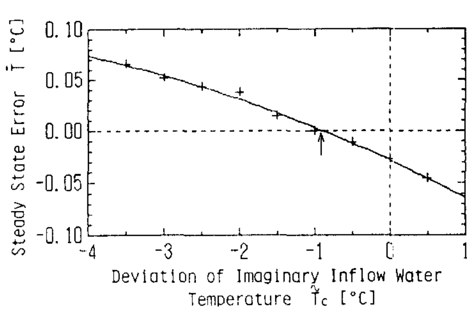

Figure 6 Relationship between imaginary inflow water temperature deviation and steady state error.

heater output 215 (cal/s) was applied until 250 (s) after the starting point, when the water temperature approached the range of 0.1 (°C). After 250 (°C), the heater output determined by (17) was used and the recursive algorithm of the (15) started at this point. To avoid a bursting phenomena of the estimation caused by the absence of a persistent excitation condition, the start-and-restart rule [14] of the recursive algorithm was applied.

Figure 7 illustrates the experimental result. We can see that the steady state of the water temperature was eliminated almost completely (compare Fig. 7(a) and Fig. 5). The transition of the estimated parameter and the imaginary heatrate are shown in Fig. 7 (b) and (c), respectively.

5. COMPARISON OF EXPERIMENTAL RESULTS BY SEVERAL METHODS

To evaluate the control performance of the proposed method relatively, we compared the experimental results by several methods: the PID controller, the servo system of the first order, and the first order servo system compensated for the drive delay.

5. 1 PID Controller

In the PID controller, the integral part (I action) works to diminish a steady state error. The manipulated variable by using the PI action is

$$U(k) = K_P\{e(k) + (1/T_I)\sum_{j=1}^{k} e(k)h\} \tag{18}$$

where K_P and T_I are the PI parameters. These parameters were determined by the ultimate sensitivity method of Ziegler-Nichols [13]. For this equipment, the values of the PI parameters were calculated as follows: $K_P = 135$ and $T_I = 83$ (s).

Figure 8(a) shows the experimental result by the PI controller. The conditions of the experiment were as follows: the initial water temperature $T = 12$ (°C), the desired water temperature $T^* = 20$ (°C), and the cooling water temperature $T_c = 12$ (°C). As seen from the figure, no steady state error exists in the water temperature, but a small oscillation can be seen and the transient response is too slow.

5. 2 Servo System of the First Order

The servo system [15] bears a stepwise change of the desired value and abrupt disturbance to the control object. The manipulated variable obtained by the first order servo system is

$$U(k) = -HX(k) + KY(k) \tag{19}$$

where $Y(k)$ is computed by the equation

$$Y(k+1) = Y(k) + \{T^* - X(k)\}. \tag{20}$$

The matrices H and K are obtained by the pole placement regulator for an augmented system [15].

Figure 8(b) shows the experimental result by using the first order servo system. The values of the poles for the augmented system were 0.95 and 0.995 respectively. Other experimental conditions were the same as those in the previous experiment. We find no steady state error but can see a significant oscillation of amplitude 0.35 (°C), which must caused by the drive delay in the water temperature system.

5. 3 The First Order Servo System Compensated for the Drive Delay

The first order servo system was improved by introducing the drive delay compensated control method. The manipulated variable by this method is

$$U(k) = -H\hat{X}(k+L) + K\hat{Y}(k+L). \tag{21}$$

The matrices H, K are the same as ones in (19). The predicted values $\hat{X}(k+L)$ and $\hat{Y}(k+L)$ are calculated by real time simulation

$$\begin{aligned}\hat{X}(k+j) &= \Phi\hat{X}(k+j-1) + D\bar{U}(k+j-1),\\ \hat{Y}(k+j+1) &= \hat{Y}(k+j) - \hat{X}(k+j),\\ j &= 1,2,3,\ldots,L.\end{aligned} \tag{22}$$

Figure 8(c) and (d) illustrate the experimental result by the first order servo system compensated for the drive delay for different pairs of the poles: (c) (0.95, 0.995), and (d) (0.95, 0.955). In case of (c), the water temperature approached the desired value appropriately and neither oscillation nor steady state error could be found. However, in case (d), where only the pole pairs were different from case (c), huge oscillation of amplitude 0.8 (°C) appeared. This method, the first order servo system compensated for the drive delay, is sensitive to the values of the poles. Usually, the appropriate selection of these poles is a hard task for a controller designer.

Through the comparison of the experiments by several methods, the proposed method, combination of the drive delay compensation and the steady state error correction, is proved to be the most accurate and convenient technique for controlling the system with drive delay.

6. CONCLUSION

We investigated a controller design for a water temperature system, with the intention of devising an accurate control

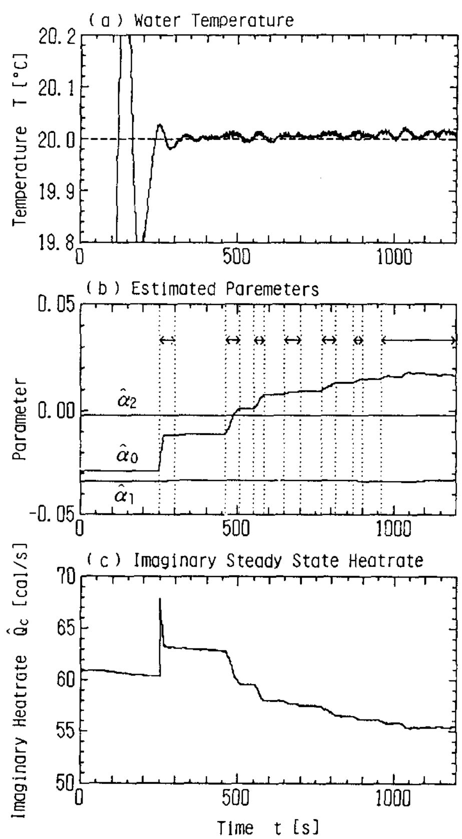

Figure 7 Experimental result for water temperature control by the proposed method: combination of compensation for drive delay and correction of steady state error.

experiment. In an experimental result based on the pole placement regulator, water temperature oscillation and steady state error appeared. The oscillation was eliminated by the drive delay compensation method, in which a future state value of the system was predicted through a real time simulation. The steady state error was eliminated by the steady state error correction, in which an actual steady state heatrate in the system model was replaced by the imaginary heatrate in real time. Through the comparison of the experiments by several methods, the PI controller, the servo system of the first order and the first order servo system compensated by the drive delay, the proposed method was proved to be the most accurate control method for the system with drive delay. The proposed systematic procedure for controller design and the countermeasure for oscillation and steady state error can be widely applicable to general industrial temperature systems.

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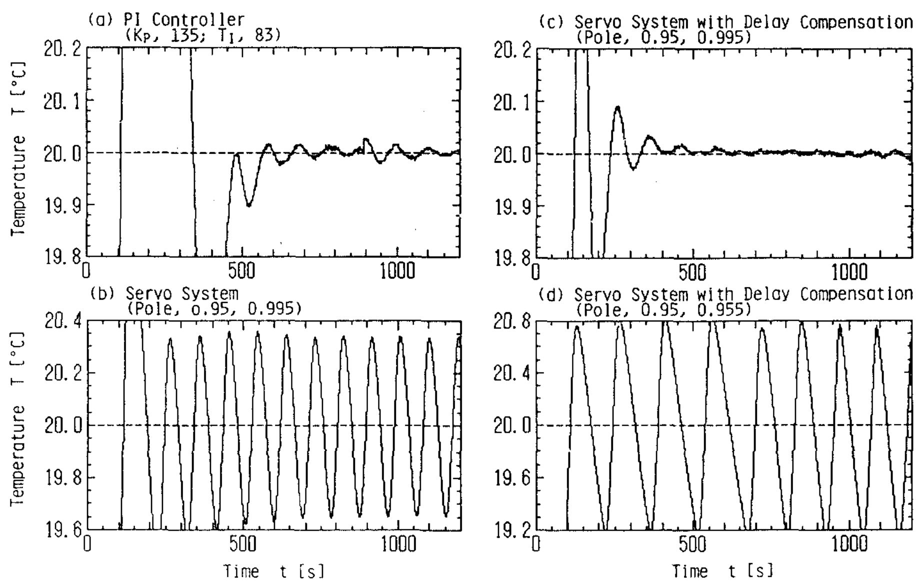

Figure 8 Comparison of experimental results by several conventional methods: (a) the PID controller, (b) the first order servo system (pole, 0.95, 0.995), (c) the first order servo system compensating for the drive delay (pole, 0.95, 0.995), (d) the same method as c (pole, 0.95, 0.955).