Model Reference Adaptive Temperature Control of the Electromagnetic Oven Process in Manufacturing Process

JIRAPHON SRIERTPOL  SUPOT PHUNGPHIMAI
School of Mechanical Engineering
Suranaree University of Technology
Address: Nakhon Ratchasima 30000
THAILAND
jiraphon@sut.ac.th

Abstract: - Nowadays, the electromagnetic ovens are used for heating the component assembly of electronic manufacturing. The control systems of the electromagnetic ovens are feedback control system and PID controller are used to control their temperature. This process is an importance process in electronics manufacturing. The problems of the electromagnetic oven are the accuracy of the temperature response when they are used in the long period of time. Examples of their problems are overshoot and high value of delay time. When the over rising of temperature occur, it leads to produce damaging. The over temperature problem is suspected that be can taken from physical changing of the electromagnetic oven. Because of this reason, PID controller parameters are not appropriate with a new condition. Therefore, the electromagnetic oven control system will have low efficiency. This paper presents the control method for any electromagnetic oven by using Model Reference Adaptive System (MRAS) to adjust the parameters of PI controller. An approximated transfer function of the electromagnetic oven obtained from closed-loop data by using nonlinear least squares method and the optimization of PID controller design is demonstrated via gradient descent method. The experimental and simulation results showed good performance in actual operations.

Key-Words: - Control Theory, Response optimization and Model Reference Adaptive System

1 Introduction
In the component assembly process of hard disk drive manufacturing has process using the adhesive with attached components. The adhesive process needs to be cured by using the electromagnetic oven that curing temperature is controlled between $T_1$-$T_2$°C for $t_2$ second. It is found that an inefficiency of required temperature control and the effect causes the damage of the products. In production line, the temperature responses of the electromagnetic oven are out of the temperature requirement and approximate 15 percent of over shoot temperature. This problem has cause from the unsuitable PID parameters that are applied in the system. This effect decreases the efficiency of temperature control. Therefore, this research has presented to apply method of the model reference adaptive system to control electromagnetic oven process. Choi J.Y. and Do, H.M.[1] analyze both structure and component of the operated process of oven by applying Tungsten-Halogen lamp to be heating source. Lord, H. A. [2] analyzes the heat transfer study with heat conduction, heat convection and heat radiation that occur inside the oven. The research of Wonhui Cho,[3] studies the heat response of system and the mathematical model for using in controller system design of oven process. Cho Wonhui Cho, Thomas F. Edgar and Jietae Lee. [4] presented the closed-loop identification of the wafer heat response by using nonlinear least squares method to find the coefficients of parameters in the mathematical model of the infrared oven process with Tungsten-Halogen lamp using the closed-loop identification method that obtains from the research of Yeo, Y K., Kwon, T. I., Lee, K. W. [5] and Pramod, S.,Chidambaram, M [6]. In an oven process, Choi, J. Y., Do, H. M., Choi, H. S. [8] and Karl J. Astrom, Bjorn Wittenmark [10] applied adaptive controller and Stephen, A. Norman,[9] presented optimization of the controller system.
2 Mathematical Model of the Electromagnetic Oven Process

The electromagnetic oven process is closed-loop temperature control system with PI-controller and has the electrical current controller for electromagnetic lamp. Inside the oven, there are thermocouples for perform temperature measurement. The mathematical model of the electromagnetic oven process can be investigated via theory of heat transfer and system identification with linearization [9]. The closed-loop control system is presented in Figure 1. The electromagnetic oven process has the delay time so we can estimate transfer function as

\[ \frac{T_p(s)}{P(s)} = G_p(s) = \frac{K e^{-ds}}{(\tau s + 1)} \]  

(1)

where 
- \( T_{des}(s) \) - desired temperature,
- \( T(s) \) - product temperature,
- \( T_a(s) \) - ambient temperature,
- \( P(s) \) - power input (lamp),
- \( K \) - gain, \( \tau \) - time constant and \( d \) - delay time

2.1 Adaptive Control System

This is an adaptive control technique where the performance specifications are given in terms of a model. A block diagram of the Model Reference Adaptive System (MRAS) is shown in Fig.2. The MRAS is to create a closed-loop controller with parameters that can be updated to change the response of the system. The output of the system is compared to a desired response from a reference model. The control parameters are update based on this error. The goal of the parameters converges to ideal values that cause the plant response to match the response of the reference model. The temperature control of the electromagnetic oven is designed a closed-loop PI-controller with MRAS.

The PI controller is

\[ G_i(s) = \left( \frac{K_p s + K_i}{s} \right) \]

(4)

The electromagnetic oven process is described by

\[ \frac{Y(s)}{U(s)} = \frac{b_2 s^2 + b_1 s + b_0}{a_2 s^2 + a_1 s + a_0} \]

(2)

The transfer function of the model reference is given by

\[ \frac{Y_m(s)}{U(s)} = \frac{\hat{b}_2 s^2 + \hat{b}_1 s + \hat{b}_0}{\hat{a}_2 s^2 + \hat{a}_1 s + \hat{a}_0} \]

(3)

where
- \( b_0 = -KK_{p} d, b_1 = KK_{p} - KK_{p} d, b_2 = KK_{p} \),
- \( a_0 = \tau - KK_{p} d, a_1 = 1 + KK_{p} - KK_{p} d, a_2 = KK_{p} \),
- \( \hat{b}_0 = -\hat{K}_{K_{p}} d, \hat{b}_1 = \hat{K}_{K_{p}} - \hat{K}_{K_{p}} d, \hat{b}_2 = \hat{K}_{K_{p}} \),
- \( \hat{a}_0 = \hat{\tau} - \hat{K}_{K_{p}} d, \hat{a}_1 = 1 + \hat{K}_{K_{p}} - \hat{K}_{K_{p}} d \) and \( \hat{a}_2 = \hat{K}_{K_{p}} \)

To derive a parameter adjustment law, we introduce the Lyapunov function

\[ V(e, \dot{e}, K_{p}, K_{i}) = \frac{1}{2} \left( \frac{\hat{a}_0}{\hat{a}_1} e^2 + \hat{e}^2 + \frac{1}{\gamma_1} (K_{p} - \hat{K}_{p})^2 \right) \]

\[ + \frac{1}{\gamma_2} (K_{i} - \hat{K}_{i})^2 \]

(7)

where \( \gamma_1 \) and \( \gamma_2 \) - adaptation gain

For the function to quality as Lyapunov function the derivative \( dV/dt \) must be negative. The stability
requirement dictate that
\[
\frac{dV}{dt} = \frac{\hat{a}_2}{\hat{a}_0} \hat{e} \hat{\ddot{e}} + \hat{e} \ddot{\hat{e}} + \frac{1}{\gamma_1} (K_p - \hat{K}_p) \hat{K}_p
\]
\[
+ \frac{1}{\gamma_2} (K_i - \hat{K}_i) \hat{K}_i
\]
\[\leq 0 \quad (8)\]
By substituting eq.(6) into eq.(8), assume \(\tau \approx \hat{\tau}, \quad K \approx \hat{K} \quad \text{and} \quad d \approx \hat{d}\), we obtain
\[
\frac{dV}{dt} = -\frac{\hat{a}_1}{\hat{a}_0} \hat{e}^2
\]
\[
+ \frac{1}{\gamma_1} (K_p - \hat{K}_p) \left\{ \hat{K}_p \frac{\gamma_1 \hat{K}}{\hat{a}_0} (\hat{\ddot{y}} - \hat{\dot{y}} + \hat{\dot{u}} + \dot{u}) \right\}
\]
\[
+ \frac{1}{\gamma_2} (K_i - \hat{K}_i) \left\{ \hat{K}_i \frac{\gamma_2 \hat{K}}{\hat{a}_0} (\hat{\ddot{y}} - \hat{\dot{y}} - \hat{\dot{u}} + u) \right\}
\]
\[\text{The parameters updates can be obtained using the following relations:}\]
\[
\hat{K}_p = -\frac{\gamma_1 \hat{K}}{\hat{a}_0} (\hat{\ddot{y}} - \hat{\dot{y}} + \hat{\dot{u}} + \dot{u}) \hat{e}
\]
\[\text{(10)}\]
\[
\hat{K}_i = -\frac{\gamma_2 \hat{K}}{\hat{a}_0} (\hat{\ddot{y}} - \hat{\dot{y}} - \hat{\dot{u}} + u) \hat{e}
\]
\[\text{(11)}\]
We get
\[
\frac{dV}{dt} = -\frac{\hat{a}_1}{\hat{a}_0} \hat{e}^2
\]
\[\text{(12)}\]
Since \(V\) is positive definite and the time derivative of the Lyapunov function is negative semi-definite then \(V(t) \leq V(0), \hat{e}, \hat{\dot{e}}, \hat{K}_p\) and \(\hat{K}_i\) will be bounded.

3 Experimental results
The adaptive algorithm of the electromagnetic oven process with MRAS using an adaptive controller based on Lyapunov’s Direct method. The parameter values of the model reference are \(\hat{K} = 5.369, \quad \hat{\tau} = 3.513\ \text{sec} \quad \text{and} \quad \hat{d} = 1.0\ \text{sec}\). We have assumed the model reference so that the percent overshoot for a step input is less than 5%, the settling time is less than 6 seconds and the rise time is less than 4 seconds when \(K_p = 0.38\) and \(K_i = 0.13\). The experiment test of the temperature response at 80°C and 90°C for step input with PI-controller can be updated to change the response of the system when \(\gamma_1 = 0.00005\) and \(\gamma_2 = 0.00001\). The initial values for this adjustment algorithm are \(K_p = 0.38\) and \(K_i = 0.13\).
Notice that the temperature response of the first electromagnetic oven in cycle 1 exhibits long settling time (8.4 sec) and initial temperature is 52 °C. After cycle 9 improving such response characteristic are desirable. The temperature response of the second electromagnetic oven in cycle 1 performs over 15.62 % of overshoot, long settling time (10.2 sec) and initial temperature is 34°C. The response after cycle 9 corrects to the same model reference response. The details of the temperature response at 80 °C are shown in Table 1.

Table 1. The temperature response of the electromagnetic oven process at 80 °C

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Maximum Overshoot (°C)</th>
<th>Percent Overshoot (%)</th>
<th>Rise time (sec)</th>
<th>Settling time (2%) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80.5</td>
<td>0.62</td>
<td>3.7</td>
<td>8.4</td>
</tr>
<tr>
<td>9</td>
<td>82</td>
<td>2.5</td>
<td>3.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>

The second experiment test considers the temperature response to step input at 90°C. Figure 7, 9 shows the plots of the step response of the electromagnetic oven process with MRAS. These temperature response curves demonstrate that the design PI controller with MRAS is acceptable. The parameter values of $K_i$ and $K_p$ for the adaptive algorithm system are indicated in Figure 8, 10.

Notice that the temperature response of the first electromagnetic oven in cycle 1, exhibits long settling time (7.3 sec) and initial temperature is 58 °C. The response of the plant converges to the response of the model reference at the cycle 6. The temperature response of the second electromagnetic oven in cycle 1, shows long settling time (8.2 sec) and initial temperature is 53°C. The cycle 9 in Fig.9 shows that the plant response converges very well. In summarizing, we show the temperature response details at 90 °C in Table 2.
Figure 10. Controller parameters $K_i$ and $K_p$ for the 2nd electromagnetic oven at 90 °C

Table 2. The temperature response of the electromagnetic oven process at 90 °C

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Maximum Overshoot (°C)</th>
<th>Percent Overshoot (%)</th>
<th>Rise time (sec)</th>
<th>Settling time (2%) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.5</td>
<td>2.77</td>
<td>3.7</td>
<td>7.3</td>
</tr>
<tr>
<td>6</td>
<td>92.8</td>
<td>3.11</td>
<td>3.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>

The temperature control of the electromagnetic oven with MRAS is to drive the error $(e = y - y_m)$ to zero. This does not necessarily imply that the PI-controller parameters approach their correct values. Notice that, the experimental results indicate that the temperature control of the electromagnetic oven in manufacturing process obtained with MRAS work as good control performance in actual operations.

## 4 Conclusion

This paper has demonstrated the model reference adaptive control method with PI controller for the electromagnetic oven process. Adjustment algorithm uses to update PI parameters of the system with Lyapunuv’s Direct Method. In order to control the temperature response follow required model reference. The results of the research presents that PI controller adjust for efficiency of the plant response to track model reference. The model reference adaptive control method can be applied to control the required temperature response for any electromagnetic oven machine and proved the existence of adaptation laws which ensure that the error equation in MRAS using an adaptive controller based on Lyapunov’s Direct method for an electromagnetic oven process is asymptotically stable.

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**References:**


