Self-tuning Curing Oven Control

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***Abstract*- Certain modern materials used in manufacturing require a specific temperature profile during the curing process to produce the desired characteristics (such as hardness). Classically, to obtain optimum control of an oven, a series of trials should be embarked on to accurately determine the coefficients of the regulator. This paper proposes a method to automatically determine the optimum parameters of the controller during the first heating process. The method has been implemented and validated in a small curing oven (3 kW). The step response and steady state error obtained were acceptable.**

I. INTRODUCTION

Temperature control in general is a well studied field. However, to control the temperature in an oven requires knowledge of the intrinsic parameters of the oven and on the other hand to be able to tune the controller for optimum results.

The temperature control of the oven is based on modeling the process which can range from a simple model to a complex/distributed model [1, 2, 5].

Previous research in this field revealed that control methods for ovens ranged from classic proportional integral (PI) control to modern artificial intelligence methods [3-10]. In [7] the control of the curing oven is based on an adaptive learning curve. Other studies present the auto-tuning of the control system based on frequency domain [11], polynomial approximation of the process [12] or extended Kalman filter [13] to determine the unknown parameters of the process.

A self-tuning algorithm based on natural/exponential temperature evolution for controlling a curing oven is proposed in this paper. It will be shown that by measuring the temperature inside the oven, the basic parameters for the controller can be determined.

The block diagram of the curing oven system under investigation is shown in Figure 1. The control method is based on oven modeling as well as continuous monitoring and extraction of the oven parameters.

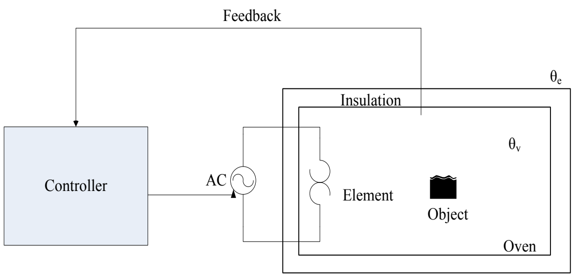

Fig. 1: Curing oven system block diagram.

II. OVEN MODELING AND VALIDATION

A. Oven Modeling

An electrical analogy for a thermal system is the *RC* time constant model. For a curing oven, the equivalent electrical diagram is as shown in Figure 2.

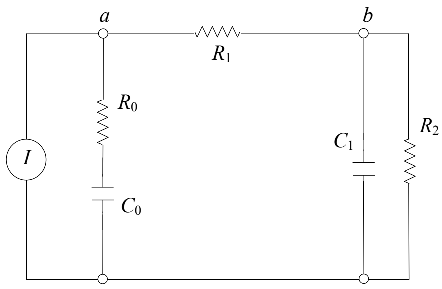

Fig. 2: Equivalent electrical model

The heat power is represented by the current generator *I* and the voltage at node *a* represents the temperature of the heat source (θ_h). The series branch R_0 C_0 represents the heat element. Resistor R_1 is the thermal impedance between the heat element and the oven. The oven itself is a reservoir of energy represented by the capacitor C_1. Resistor R_2 represents the losses through the oven walls. Practical measurements show that the heat element branch influence is negligible and can be ignored. The equivalent model can thus be simplified to that shown in Figure 3.

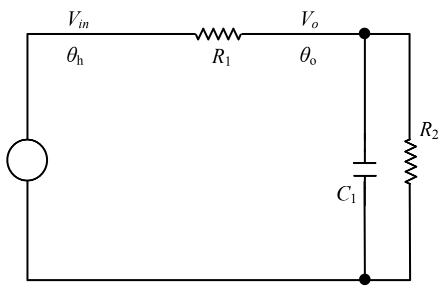

Fig. 3: Simplified model of the curing oven

Applying KVL for this model the relationship between the parameters of the model is given by:

$$v_{in}(t) = \left(1 + \frac{R_1}{R_2}\right) v_o(t) + R_1 C_1 \frac{dv_o}{dt} \tag{1}$$

The solution of this differential equation is:

$$v_o(t) = \frac{R_2 v_{in}}{R_1 + R_2}\left[1 - \exp(-t/\tau)\right] \quad (2)$$

Where:

$$\tau = \frac{R_1 R_2 C_1}{R_1 + R_2} \quad (3)$$

Applying the duality theorem between the electrical and the thermal circuit, equation (3) becomes:

$$\theta_o(t) = R_2\left(\frac{V_s^2}{R_{eh}}\right)\left[1 - \exp(-t/\tau)\right] \quad (4)$$

Where: V_s is the supply voltage and R_{eh} is the heater element.

The parameter τ from equation (4) is the same as in equation (3) but now R_1 is the thermal resistance of the air (which is generally a known parameter), R_2 is the thermal resistance of the insulation and C_1 is the heat capacity of the oven. It can be observed that the oven temperature depends on the electric power applied and the parameters of the oven. Thus, to control the oven temperature given the oven parameters, only the electric power needs to be controlled.

B. Oven Model – Experimental Validation

The data collected by the logger has been imported in a Matlab platform and the measured curve was built. Then, using the theoretical expectation (equation 4) and a curve fitting tool, the simulated curve resulted. The experimental measurements in Figure 4 reveal a fairly good validation with that of the mathematical model. It can be noticed that a significant difference exists at the origin of the graph due to the transient nature of the system and the degree of simplification. However, under steady state conditions in the area of interest, the experimental results follow the mathematical model closely.

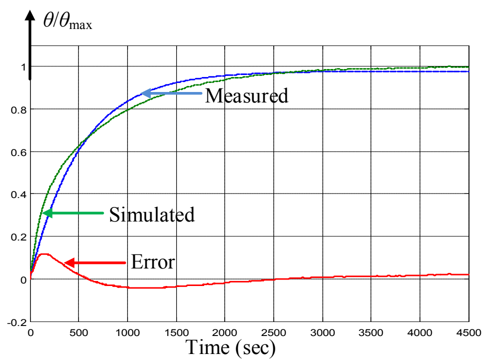

Fig. 4: Experimental model validation of the oven under investigation

III. Control System

A. Integral-Proportional Controller

In this research, a simple IP controller was implemented in order to validate self-tuning based on extracting the relevant control parameters from only one set of measurements. This could lead to using the same technique to extract control parameters for more sophisticated control methods such as digitized PID, neural networks, fuzzy logic, etc.

The block diagram for the controller is shown in Figure 5. The plant, according to the mathematic model, is of first order with constant τ given by (3); the low pass filter (parameter ξ being the filter time constant which much smaller then τ) is introduced to minimize the noise influence.

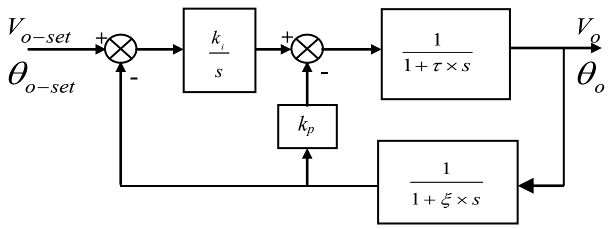

Fig. 5: Block diagram of IP controller

Considering the equivalent model, the closed loop transfer function of the system is:

$$\frac{V_o}{V_{o-set}} = \frac{1 + s \times \xi}{s^3\left(\frac{\xi \times \tau}{k_i}\right) + s^2\left(\frac{\xi + \tau}{k_i}\right) + s\left(\frac{k_p}{k_i}\right) + 1} \quad (5)$$

The poles of the system (s_0, s_1 and s_2) are placed on the Butterworth circle (Figure 6) with the radius ω_o.

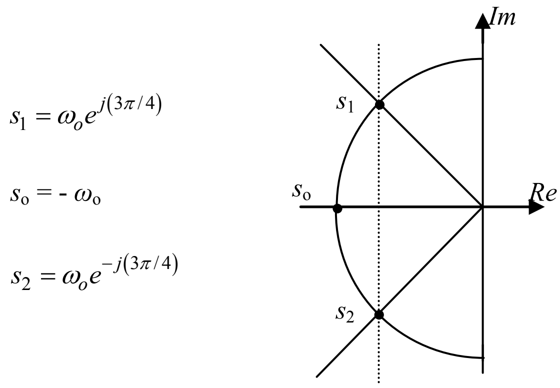

Fig. 6: Pole placement of IP controller

With the assumption of the poles placed on the Butterworth circle [14] and the equivalent diagram of the oven, the proportional and integral coefficient should be:

$$k_i = \frac{(T+\xi)^3}{T^2\xi^2\left(1+\sqrt{2}\right)^3 R} \tag{6}$$

$$k_p = \frac{1}{R}\left(\frac{(T+\xi)^2}{\left(1+\sqrt{2}\right)T\xi} - 1\right) \tag{7}$$

$$\omega_o = \frac{T+\xi}{T\xi(1+\sqrt{2})} \tag{8}$$

Where:

$$T = RC_1 \tag{9}$$

$$R = R_2^2 / \left(R_1 + R_2\right) \tag{10}$$

As expected, the coefficients of the regulator depend on the actual parameters of the oven.

B. Self-Tuning Algorithm

The proposed self-tuning consists of determining the parameters of the oven (C_1, R_1 and R_2) from measurement of the oven temperature (θ_{ov}). The known parameters are the air thermal resistance (R_1), supply voltage (V_s) and the electrical resistance of the heater (R_{eh}). The experimental graph in Fig. 4 closely resembles the mathematical model of Eq. (4). In the practical range of temperatures, the error was acceptable. The basic parameters of the oven can be extracted by using Eq. (4) and the actual measurements. This relation (4) reveals an interconnection between the oven temperature and unknown parameters (C_1 and R_2). A numerical approach was used to solve for the unknown parameters. The data logger averaged a number of readings to obtain a noise free sample every Δt = 10 sec. Two consecutive samples were used to determine the oven parameters. For this sampling time which is much smaller then the time constant of the process, the variation of the temperature is linear:

$$\theta_o\left(t_k + \Delta t\right) = \frac{\Delta t}{\tau}\theta_o\left(t_k\right) \tag{11}$$

The flow chart of the process is shown in Figure 7. Due to the larger error during start-up it was decided to activate the algorithm when the temperature rises above 100 °C. The parameters of the oven result as R_1 = 1.536 W/K, R_2 = 134.4 and C_1 = 131.1 J/K. The end result of the proposed algorithm provides the values of the proportional and integral parameters for the oven controller. For the study case of this paper the controller parameters obtained with the proposed algorithm were K_i = 13.36 and K_p = 1.023.

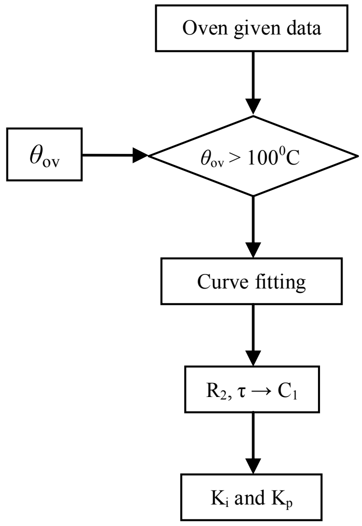

Fig. 7 Control parameters extraction algorithm

IV. Experimental Results

A. Experimental Setup

The oven is shown in Fig. 8 with the auto transformer and other measuring equipment.

Fig. 8 Experimental setup.

B. Power Controller (Power switch)

The switching element in this experiment was a combination of a classic relay and a triac in order to eliminate power loss in the triac and EMI during switching. Fig. 9 shows the zero crossing switch-ON and -OFF transients. The triac initially switches on while the relay is sluggish to respond. When the relay has switched ON, the triac switches OFF but the load stays energized. At switch-OFF the triac is switched on while the relay is being released and then the triac switches OFF at the next zero crossing.

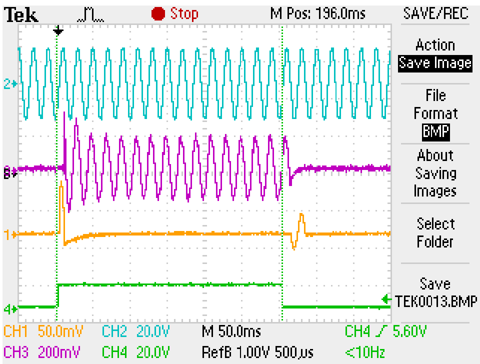

Fig. 9 Switching oscillogram.

C. Steady temperature control

This experimental model was tested for a step response only. At this stage no curing profile has been implemented. The temperature was set to 350 °C. The actual control presented in section 3 was implemented in a microcontroller and the result of the step response is shown in Fig. 10.

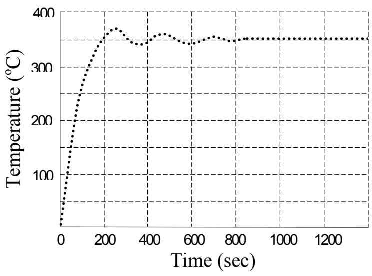

Fig. 10 Step response for 350 °C set point.

The over-shoot is reasonable (7%) and the steady-state error is below 2%.

V. CONCLUSIONS

The realization of a mathematical model of an oven from a set of temperature measurements makes it feasible to build a universal controller for (curing) ovens that will be "self-learning". The first time the controller is used to heat the oven, it goes into a setup mode in order to determine the unknown oven parameters R_2 (thermal insulation) and C_1 (thermal energy storage). Thereafter, the controller interface allows the user to set up the temperature profile of the curing process to be followed.

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