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스텝응답을 이용한 3매개변수 모델의 식별

Identification of Three-Parameter Models from Step Response

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Abstract: This paper provides an identification method for three-parameter models i.e. first order with dead time models and second order with dead time models. The proposed identification method is based on step response and can be easily implemented using digital microprocessors. The proposed method first identifies the order of the plant i.e. first order or second order from the behavior of the plant with constant input. After the order of the plant is determined, a test step input is applied to the system and the three parameters of the plant are obtained from the corresponding response of the plant. The output of the plant need not to be zero when the test signal is applied. The efficacy of proposed algorithms is verified through simulation and experiment.

Keywords: first/second order model, parameter identification, step response, time delay

I. INTRODUCTION

Process dynamics can be estimated based on the measurement of the process responses obtained from the test input signals such as pulse, step, ramp and other deterministic signals. Among the various test signals, step response has received a particular attention due to its simplicity and easy implementation [1]. It is widely used in industrial processes for tuning the PID controllers; e.g. Ziegler-Nichols step response method [2,3]. Astrom and Haggluned [1] demonstrated the identification of plants of first/second-order with time-delay using a graphical method to identify the plant parameters. Some other graphical methods are proposed using step responses [4,5] and frequency responses [4]. However, these graphical methods would be inaccurate, especially in the presence of noise. Furthermore, they require that the initial output of the plant and its initial derivatives are zero before the application of test signals.

An identification method which takes nonzero initial conditions into account for nth order plant was reported by Mathew and Fairman [6] based on impulse response and they did not consider dead-time which is unavoidable in industrial processes. Other identification methods [7-11] were developed for models of first order with dead time. They require that the output and its derivative should be zero before the application of step signal. Another popular approach was based on feedback test [11-13] to identify the parameters of models with various orders. But in these methods iteration was included, which prolongs the time of identification of the parameters.

In this paper, a simple system identification method based on the step response is proposed for the first/second order plant with a time delay and it does not require iteration. The step input can be applied to a plant for identification while its output is non-zero. The proposed method is an extension of the parameter identification part of the auto-tuning of PID/PIDA controllers based on step-response proposed in [14]. Two different types of plant models will be considered. The identification algorithms for each types of plant are slightly different. So, we also provide an algorithm to determine which plant model will be assumed. It will be easy to implement the proposed method using microprocessor. We described how to implement the proposed algorithm using Stateflow of SIMULINK and proposed experiment results which apply the proposed algorithm to the heater of hot runner.

II. PROCESS MODELS AND THE IDEA OF PARAMETER IDENTIFICATION

We consider two representative types of system models, which are represented by the transfer-function G(s) as:

$$G(s) = \frac{K}{s^m (Ts+1)} e^{-Ls}, \tag{1}$$

where m=0 or 1. The systems have dead time and are characterized by three parameters, K, L(L>0) and T(T>0), where K is the static process gain, L is the dead time and T is the time constant. We will consider the cases in which m=0 and m=1 separately.

1. Model without integrator case (m=0)

Let's assume temporarily that the dead time is zero i.e. L=0. Then the Laplace transform of the step response of system (1) with step input size 'a' can be written as:

$$Y(s) = \frac{aK}{s(Ts+1)}. \tag{2}$$

After simple manipulations on (2), the following relation is obtained,

$$(Ts^2 + s)Y(s) = aK. \tag{3}$$

Note that the transfer function and the output (2) (or (3)) are

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given on the assumption that $y_0 = 0$ and $y_0' = 0$, where y_0 and y_0' represent $y(0)$ and $\left.\frac{dy(t)}{dt}\right|_{t=0}$, respectively. In the case of non-zero initial conditions i.e. $y_0 \neq 0$ and $y_0' \neq 0$, (3) can be rewritten by using the initial value theorem of the Laplace transform, as follows:

$$Y(s) = \frac{aK + y_0 + Tsy_0 + Ty_0'}{s(Ts+1)}. \tag{4}$$

The partial fraction expansion of equation (4) is,

$$Y(s) = \frac{l_1}{s} + \frac{l_2}{Ts+1}, \tag{5}$$

where

$$\begin{aligned} l_1 &= aK + Ty_0' + y_0, \\ l_2 &= Ty_0 - l_1 T. \end{aligned} \tag{6}$$

Employing the inverse Laplace transform of (5), the output in time domain is obtained as,

$$y(t) = l_1 + \frac{l_2}{T} e^{-t/T}, \quad (t \geq 0). \tag{7}$$

As time 't' increases, the $e^{-t/T}$ becomes zero and (7) reduces to,

$$y(t) \cong l_1, (t >> T). \tag{8}$$

From (6) and (8), the process gain can be found as,

$$K = \frac{y(\infty) - Ty_0' - y_0}{a}, \tag{9}$$

where $y(\infty)$ represents the $y(t)$ for some t such that $|e^{-t/T}|$ is very small. Here the T is an unknown parameter. So, in order to find out the gain K, we assume that $\left.\frac{d^i y(t)}{dt^i}\right|_{t=0}$, $(i \geq 1)$, then the equation (9) becomes,

$$K = \frac{y(\infty) - y_0}{a}. \tag{10}$$

On the other hand, taking derivative of $y(t)$, the equation (7) becomes,

$$\begin{aligned} y'(t) &= -\frac{l_2}{T^2} e^{-\frac{t}{T}}, \\ y'(t) &= -\frac{1}{T}(aK + Ty_0')e^{-\frac{t}{T}}, \end{aligned} \tag{11}$$

by making use of (6). Here we also assume that $y_0' = 0$.

From (11) we can see that $y'(t)$ get the maximum value when t=0. On the other hand when t=T the value of $e^{-t/T}$ becomes 0.367. Parameter, T is obtained from the time difference between the time index of the maximum value of $y'(t)$ and that of 36.7% decay from the maximum of $y'(t)$. The relation becomes,

$$y'(T) = y_{\max}' \times 0.367. \tag{12}$$

Now let's consider nonzero time delay i.e. $L \neq 0$. It is easy to see that (10) still hold true and $y'(t)$ of (11) will take the maximum at t=L. Thus the time delay L can be estimated as the consumed time to reach the maximum value of $y'(t)$. From the equation (12) the time delay can be defined as,

$$L = t_{\max}, \tag{13}$$

where t_{max} represents the elapsed time to reach the maximum $y'(t)$ from the application of step signal , under the condition $\left.\frac{d^i y(t)}{dt^i}\right|_{t=0} = 0, \ (i \geq 1).$

2. Model with integrator case (m=1)

Let's assume temporarily that the dead time is zero i.e. L=0. Then the Laplace transform of the step response of system (1) with amplitude 'a' of input step can be written as:

$$Y(s) = \frac{aK}{s^2(Ts+1)}. \tag{14}$$

After manipulations on (14), the following relation is obtained,

$$(Ts^3 + s^2)Y(s) = aK. \tag{15}$$

Note that the transfer function and the output (14) (or (15)) are given on the assumption that $y_0 = 0, y_0' = 0,$ and $y_0'' = \left.\frac{d^2 y(t)}{dt^2}\right|_{t=0} = 0$. In the case of non-zero initial conditions i.e. $y_0 \neq 0, y_0' \neq 0,$ and $y_0'' \neq 0$, (15) can be rewritten by using the initial value theorem of the Laplace transform, as follows:

$$Y(s) = \frac{aK + s^2 Ty_0 + s(Ty_0' + y_0) + (y_0' + Ty_0'')}{s^2(Ts+1)}. \tag{16}$$

The partial fraction expansion of equation (16) is,

$$Y(s) = \frac{l_1}{s^2} + \frac{l_2}{s} + \frac{l_3}{Ts+1}, \tag{17}$$

where

$$\begin{aligned} l_1 &= Ty_0'' + y_0' + aK. \\ l_2 &= Ty_0' + y_0 - l_1 T. \\ l_3 &= Ty_0 - l_2 T. \end{aligned} \tag{18}$$

Employing the inverse Laplace transform of (17), the output in time domain is obtained as,

$$y(t) = l_1 t + l_2 + \frac{l_3}{T} e^{-t/T}, \tag{19}$$

by taking derivative of $y(t)$, the equation (19) becomes,

$$y'(t) = l_1 - \frac{l_3}{T^2} e^{-t/T}. \tag{20}$$

As time 't' increases, the e-t/T becomes zero and (20) reduces to,

$$y'(t) \cong l_1, (t >> T). \tag{21}$$

From (18) and (21), the process gain can be found as,

$$K = \frac{(y'(\infty) - Ty_0'' - y_0')}{a}, \quad (22)$$

where $y'(\infty)$ represents the $y'(t)$ for some time such that $|e^{-t/T}|$ is very small . Here the T is an unknown parameter. So, in order to find out the gain K, we assume that $\left.\frac{d^i y(t)}{dt^i}\right|_{t=0}, (i \ge 2)$, then the equation (22) becomes,

$$K = \frac{y'(\infty) - y_0'}{a}. \quad (23)$$

On the other hand, by taking derivative of $y'(t)$, the equation (20) becomes,

$$y''(t) = \frac{l_3}{T^3}e^{-t/T}, \quad y''(t) = (y_0'' + \frac{aK}{T})e^{-t/T}, \quad (24)$$

by making use of (18), Here we also assume that $y_0'' = 0$.

From (24) we can see that $y''(t)$ get maximum value when t=0, on the other hand when t=T, the value of $e^{-t/T}$ becomes 0.367. Parameter, T is obtained from the time difference between the time indexes of the maximum value of $y''(t)$ and that of 36.7% decay value from the maximum of $y''(t)$. The relation becomes,

$$y''(T) = y''_{max} \times 0.367. \quad (25)$$

Now let's consider nonzero time delay i.e. $L \ne 0$. It is easy to see that (23) still hold true and $y''(t)$ of (25) will take maximum at t=L. Thus the time delay L can be estimated as the consumed time to reach maximum value of the $y''(t)$. From the equation (25) the time delay can be define as

$$L = t_{max}, \quad (26)$$

where t_{max} represents the elapsed time to reach the maximum $y''(t)$ from the application of step signal, under the condition $\left.\frac{d^i y(t)}{dt^i}\right|_{t=0}, (i \ge 2)$.

III. PARAMETER IDENTIFICATION ALGORITHM

The identification algorithm is total in seven steps for both first and second order models, are implementable by using digital microprocessor. However, identification methods for the system parameters are slightly different with respect to plant order. By using the low-pass filter the noises and disturbance are reduced from the plant output, then applying the parameter identification algorithm. Since in real plant, it is hard to detect y'(t) and y''(t) equal to zero, thresholds δ_1 and δ_2 in the algorithm are considered for appropriate identification. Steps of the parameter identification algorithm are given below,

1. Parameters identification algorithm for m=0.

Para_Id_Algorithm_0:

Step 1: At non-zero initial position based on input signal, u=0 of the system, wait and observes the output become $|y'(t)| < \delta_1$ ($0<\delta_1<<1$).

Step 2: When step 1 satisfied, set time t=0 and save the value of y(0), then apply step input of the system with step size 'a'.

Step 3: When y'(t)> δ_1, determine the time t, by using equation (13) the measured time become the parameter L.

Step 4: At y'(t) have maximum value, save time as t_{max} and the output value of $y'(t_{max})$.

Step 5: According to the equation (12) measure 36.7% decayed value of y'(t) from the time t_{max} (step 4), this time range($t \sim t_{max}$) is represent the parameter T.

Step 6: |y'(t)| become decreases in time, measure the value of the y(t) when time goes $|y'(t)|<\delta_2$, ($\delta_1<\delta_2<<1$), from step 2 we got value of y(0) and the step input size 'a'. Now use equation (10) to determine the parameter K.

Step 7: Stop the step input, the identification of the parameters are completed.

2. Parameters identification algorithm for m=1.

Para_Id_Algorithm_1:

Step 1: At non-zero initial position based on input u=0 of the system, wait and observes the output become $|y''(t)| < \delta_1$, ($0<\delta_1<<1$).

Step 2: When step1 satisfied, set time t=0 and save the value of y'(0), then apply step input of the system with step size 'a'.

Step 3: When y''(t)> δ_1, determine the time t, by using equation (26) the measured time become the parameter L.

Step 4: At y''(t) have maximum value, save time as t_{max} and the output value of $y''(t_{max})$.

Step 5: According to the equation (25) measure 36.7% decayed value of y''(t) from the time t_{max} (step 4), this time range($t \sim t_{max}$) represent the parameter T.

Step 6: |y''(t)| become decreases in time, measure the value of y'(t) when time goes $|y''(t)|<\delta_2$, ($\delta_1<\delta_2<<1$), from step 2 we got y'(0) and step input size 'a'. Now use equation (23) to determine the parameter K.

Step 7: Stop the step input, the identification of the parameters are completed.

The above identification algorithms Para_Id_Algorithm_0 and Para_Id_Algorithm_1 are used for identification of the plant parameters. In the first order with dead time (FODT) model, the parameters are identified by using the equations (10), (12) and (13). In order to apply system identification algorithm, one of the necessary condition is $y'(t) = 0$. On the other hand, second order integral model with dead time (SODT) the parameters are identified based on equations (23), (25) and (26) and $y''(t) = 0$, must be satisfied. Low pass filter is used to remove the contained noise at output of y(t), y'(t) and y''(t).

3. Plant order identification algorithm

For non-zero initial state plant, the plant order identification algorithm consists of three steps. The steps are given below,

Order_Id_Algorithm:

Step 1: Generate and apply a constant input as small as possible to the system.

Step 2: Wait until the second derivative of the output becomes sufficiently small i.e.

$$|y''(t)| \le \delta_1, \tag{27}$$

for all $t \ge t_1 \ge 0$, where δ1 is a small positive value and t_1 is the time from which (27) satisfied.

Step 3: After t_1, wait further for some predetermined period T to see that the first derivative of the output decrease to zero or not.

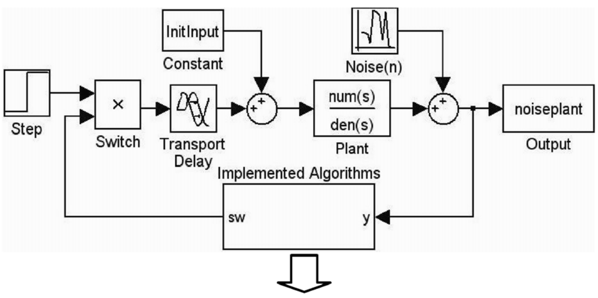
$$\text{if } |y'(t_1+T)| < \delta_2,$$

we set the order of the plant as 1 i.e. M=1, other wise we set M=2.

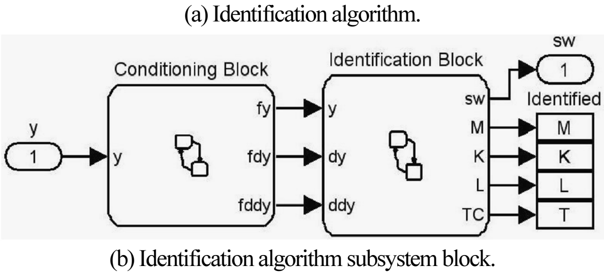
By applying plant order identification algorithm, we will get the order of the target plant, which give the value of m, to determine the algorithm Para_Id_Algorithm_0 in 3.1 or Para_Id_Algorithm_1 in 3.2 should be applied. Note that the step 1 of Para_Id_Algorithm_0 and Para_Id_Algorithm_1 can be replace by Orer_Id_Algorithm.

IV. IMPLEMENTATION OF THE ALGORITHM USING STATEFLOW OF MATLAB SIMULINK.

As it can be shown in Fig. 1, we did simulation studies using MATLAB SIMULINK. The step input signal is generated by step function block. The process plant is represented by continuous time transfer function blocks. Time delay is defined as a continuous transport delay function. The generated disturbance noise is denoted by random number (±n). The outputs are observed by using the workspace block. The identification algorithm proposed in section III is implemented as a subsystem block, which contains two Stateflow chart blocks, i.e. conditioning block and identification block. The Stateflow chart is a tool of MATLAB SIMULINK, which is widely used in model based development of embedded systems. The Stateflow consists of ‘state’ and ‘transition’ and they can be transformed into C-code easily for micro-processor implementation.



(a) Identification algorithm.



(b) Identification algorithm subsystem block.

그림 1. 시스템식별을 위한 SIMULINK 다이어그램.

Fig. 1. SIMULINK diagram for system identification algorithm.

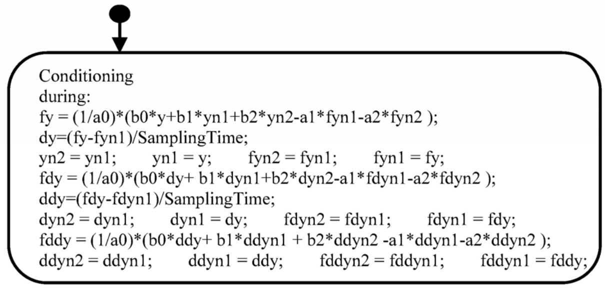


그림 2. 컨디셔닝 블록의 상태.

Fig. 2. State of conditioning block.

1. Conditioning block.

Conditioning block shown in Fig. 1(b), has one input signal y and three outputs signals fy, fdy and fddy, where y is output signal of the plant. We considered an infinite impulse response (IIR) Butterworth filter to reduce the unwanted disturbance and noise signals. The transfer function of the filer is given by:

$$FY(z) = H(z)X(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}} Y(z)$$

This corresponds to a time domain recurrence relation:

$$\begin{aligned} fy(n) = \frac{1}{a_0}\{&-a_1 fy(n-1) - a_2 fy(n-2) + b_0 y(n) \\ &+ b_1 y(n-1) + b_2 y(n-2)\} \end{aligned} \tag{28}$$

The a0, a1, a2, b0, b1 and b2 are the coefficients of the filter. The fy, fdy and fddy signals represent the filtered value of y, dy and ddy, where dy and ddy are computed as $dy(k) = \frac{fy(k) - fy(k-1)}{T}$, and $ddy(k) = \frac{fdy(k) - fdy(k-1)}{T}$ respectively, where T denotes the sampling time. Fig. 2 shows the detail of conditioning block which carries out the computation of fy, fdy and fddy signals.

At every sampling time the conditioning state shown in Fig. 2, is executed to update data. The coefficients of the filter (28) were obtained by using ‘butter’ command at MATLAB command prompt with cutoff frequency 0.01Hz.

2. Identification block

The Identification block has three inputs and one output signal as shown in Fig. 1(b). They can be divided into four parts to describe the flow of implementations. The four parts of the identification algorithm are described below:

2.1 Identification of the plant order

While step 1 of the Order_Id_Algorithm is carried out by constant block of Fig. 1(a). Step 2 and 3 of the Order_Id_Algorithm are implemented by using the ‘transition’ as Fig. 3. The ‘transition’ can be translated into C-code easily using an if clause.

When the variable State is ‘1’ the procedure is in the step 2 of Order_Id_Algorithm, here the condition |y''(t)|≤ δ1 is checked. State==2 means the procedure is in the step 3 of Order_Id_Algorithm. If the State==3, the order of the plant is determined and make braches to Para_Id_Algorithm_0 or Para_Id_Algorithm_1

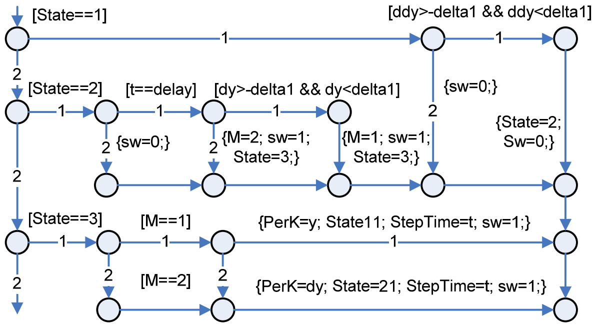


그림 3. 플랜트 식별.

Fig. 3. Identification order of the plant.

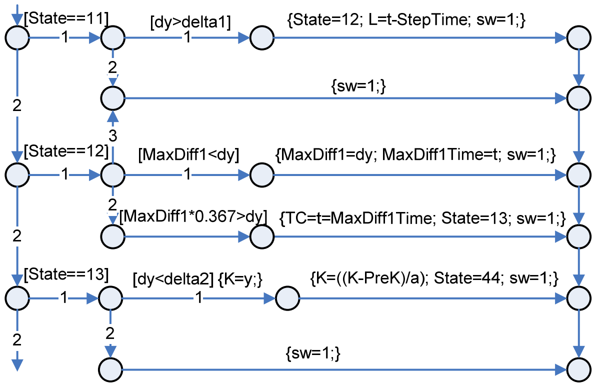


그림 4. 파라메터 식별알고리즘 (m=0).

Fig. 4. Parameters identification algorithm (m=0).

The flow of transition segments select the parameters identification algorithm based on identified order i.e., M=1 or M=2. . If M==1 the step 2 of Para_Id_Algorithm_0 otherwise if M==2 the step 2 of Para_Id_Algorithm_1 is proceed.

2.2 Parameters identification algorithm for m=0.

If State==11 in Fig 4, the procedure is in the step 3 of Para_Id_Algorithm_0 algorithm. When State==12, the procedure is in the steps 4 and 5 of Para_Id_Algorithm_0 algorithm. And State==13 means the procedure is in the step 6 of Para_Id_Algorithm_0 algorithms.

2.3 Parameters identification algorithm for m=1.

If M=2 is selected at State==3 junction of Fig. 3, the execution flow comes to State==21, the procedure is in the step 3 of Para_Id_Algorithm_1 algorithm.

Now in State==22, the procedure is in the steps 4 and 5 of Para_Id_Algorithm_0 algorithm. The State variable '23' means the procedure is in the step 6 of Para_Id_Algorithm_0 algorithm.

2.4 Ending of the algorithm

If State==44 in Fig. 6, the procedure set sw=1, otherwise the procedure will set sw=0, finally the transition will go to the last junction. When the transition executes the last junction which contains no outgoing transition segments, chart execution is complete.

When the state is 44, it means that the parameter identification is finished.

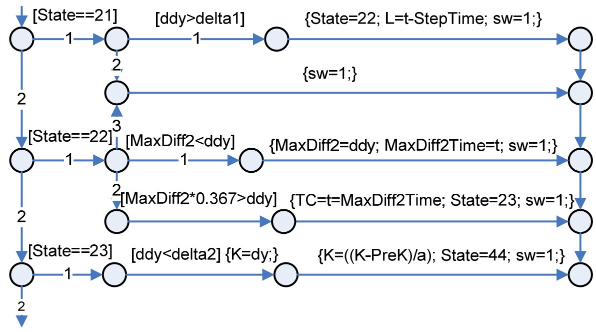


그림 5. 파라메터식별 알고리즘(m=1).

Fig. 5. Parameters identification algorithm (m=1).

그림 6. 스테이트 플로우 챠트 종료.

Fig. 6. Ending of the Stateflow chart.

V. SIMULATION RESULTS

We considered five different set of parameters for each of FODT and SODT models. The simulation results of Order_Id_Algorithm, Para_Id_Algorithm_0 and Para_Id_Algorithm_1 algorithms are shown below.

1. Test result for plant order identification

The proposed order identification algorithm identified the order of FODT and SODT model plants correctly in every test.

2. Test results for FODT model (m=0)

The system identification algorithm is applied to FODT models with disturbance magnitude ±0.01 and its results are shown in Table 1.

For the third model of the Table 1, the system identification algorithm is also applied with different magnitude range of

표 1. FODT 모델 식별결과.

Table 1. Results of system identification (FODT).

Models	Real Values			Estimated Values		
	K	T	L	K	T	L
(1)	5.2	1.9	4.3	5.245	3.50	3.55
(2)	4.6	2.8	1.3	4.624	3.65	2.25
(3)	4	5	7	3.971	4.30	5.40
(4)	1.6	2.8	5.7	1.603	3.75	5.10
(5)	0.8	7.3	2.6	0.789	5.05	5.35

표 2. 다양한 외란 하에서의 파라메터 식별 결과(FODT).

Table 2. Result of parameters identified with different magnitude range of disturbance (FODT).

Parameter	Real Values	Estimated Values		
		0	±0.01	±0.02
K	4	3.98	3.97	3.96
T	5	4.25	4.30	4.30
L	7	5.40	5.40	5.40

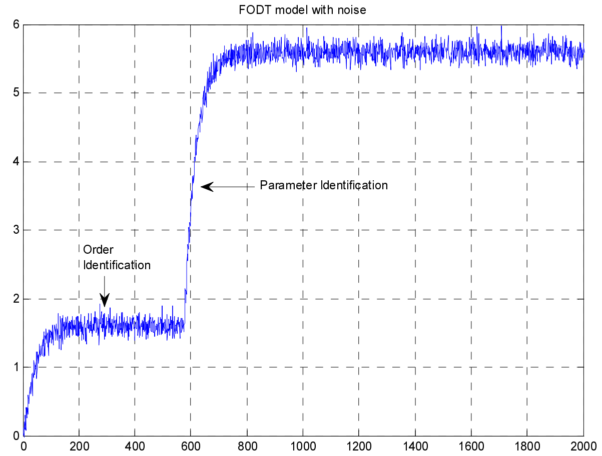


그림 7. FODT 모델출력.

Fig. 7. Output of FODT model.

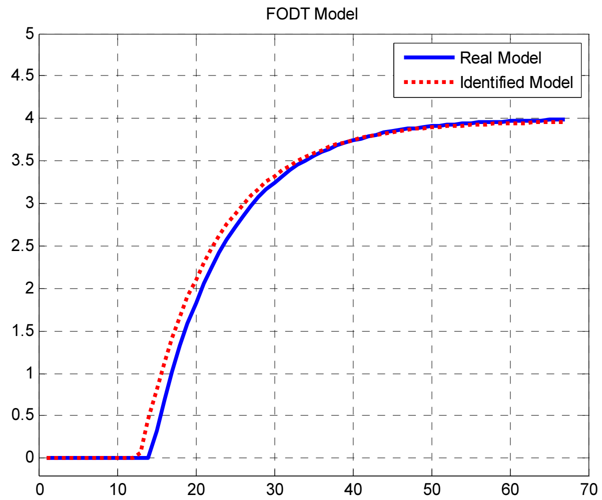


그림 8. FODT 모델 식별결과.

Fig. 8. Result of system identification (FODT).

disturbances i.e. 0, ±0.01, and ±0.02, and the results are summarized in Table 2.

The plant output during the order and parameter identification for a step input response of FODT model is shown in Fig. 8.

Note that the Para_Id_Algorithm_0 can be applied when the output is non zero. The real model and identified model are compared in the Fig. 9.

3. Test results for SODT model (m=1)

The system identification algorithm is applied to SODT models with disturbance magnitude ±0.01 and its results are shown in Table 3.

The system identification algorithm is also applied with different magnitude range of disturbance i.e. 0, ±0.01, and ±0.02 for the third SODT model and the results are summarized in Table 4.

The plant output during the order and parameter identification for a step input response of SODT model is shown in Fig. 10. Note that the Para_Id_Algorithm_1 can be applied when the output is non zero.

표 3. SODT 모델식별결과.

Table 3. Results of system identification (SODT).

Models	Real Values			Estimated Values		
	K	T	L	K	T	L
(1)	5.2	1.9	4.3	5.469	3.50	3.65
(2)	4.6	2.8	1.3	4.778	3.65	2.40
(3)	4	5	7	5.015	4.20	5.50
(4)	1.6	2.8	5.7	1.662	3.70	5.20
(5)	0.8	7.3	2.6	0.801	4.90	5.40

표 4. 다양한 외란 하에서의 파라메터 식별 결과 (SODT).

Table 4. Result of parameters identified with different range of disturbance (SODT).

Parameter	Real Values	Estimated Values		
		0	±0.01	±0.02
K	4	4.01	4.01	4.01
T	5	4.25	4.20	4.20
L	7	5.65	5.65	5.65

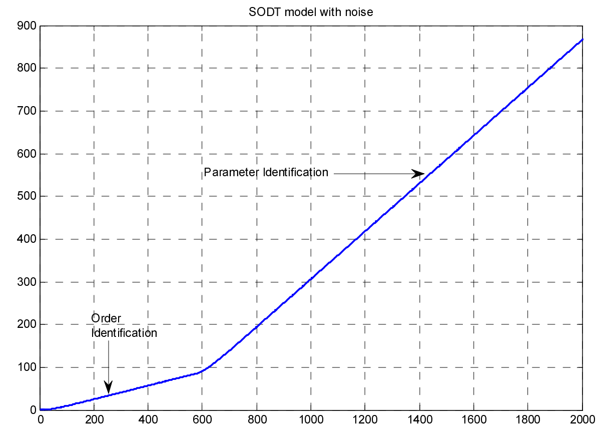


그림 9. SODT 모델 출력.

Fig. 9. Output of SODT model.

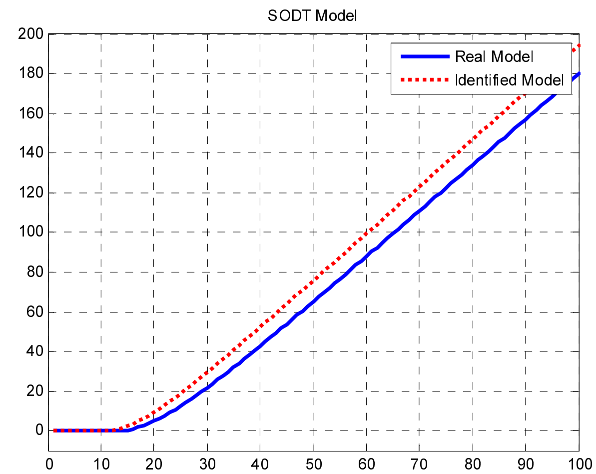


그림 10. SODT 모델 식별결과.

Fig. 10. Result of System identification (SODT).

The real model and identified model are compared in the Fig. 11.

The test results are shown in Fig. 9 for FODT model and in Fig. 11 for SODT model, where solid line indicates the output of the real process model and dashed line is from the identified process model. The simulation output matches with considered model quite well in presence of measuring noise.

VI. EXPERIMENTAL RESULTS

The experimental model setup shown in Fig. 12, was tested in our lab. For our experiment, we considered three different heaters for hot runners i.e. 1110W, 367W and 226W. We implemented the proposed identification method using ARM920T processor [15]. For each hot runner, the algorithms were applied ten times. The result of order identification algorithm gives 2 for all plants because the output behavior of all the plants similar to SODT model. The experimental results for hot runners are summarized in Table 5.

The experimental results are shown in Fig. 13.

The experimental results are shown in Fig. 13 for three different heaters for hot runners indicate by '□', '*' and 'o'. Where '□' indicates the 1110W hot runner, '*' indicates 367W hot runner and 'o' indicates 226W hot runner. The experimental results of the identification method, works quit well in real life application.

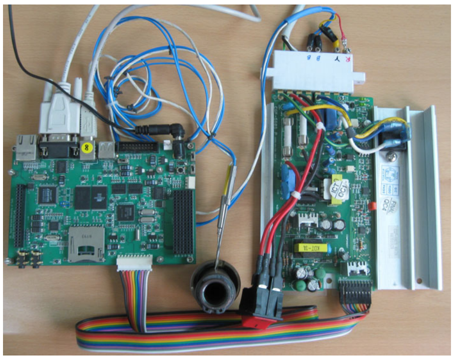


그림 11. ARM 기반 실험장치.

Fig. 11. Experimental model setup of ARM system.

표 5. 핫런너 실험결과.

Table 5. Experimental results of hot runners.

Heater	K	T	L
1110 W	0.0017	4.6860	4.3020
367 W	0.0057	3.0580	1.0670
226 W	0.0035	2.6501	1.3360

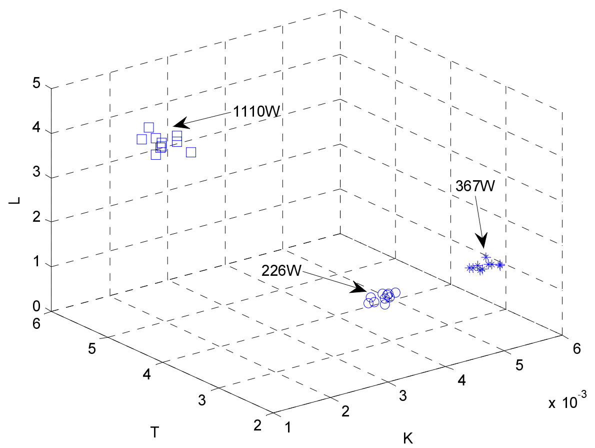


그림 12. 실험결과.

Fig. 12. Experimental results.

VII. CONCLUSIONS

In this paper, a method to indentify parameters and order of three parameter model with time delay has been proposed. This method is based on step test signal and is robust to noise. The computation is straight forward and no iteration is required to indentify the parameters. This method does not require complex mathematical calculations and it can be implemented by using digital microprocessor. The effectiveness of the proposed order and parameter identification method has been demonstrated by using MATLAB simulation and real life experimental results of the heater of hot runner.

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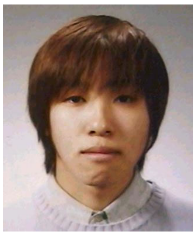

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