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# 데이터 기반 저차제어기 설계: 모멘트 정합 기법

## Data Based Lower-Order Controller Design: Moment Matching Approach

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(Young Chol Kim · Lihua Jin)

**Abstract** - This paper presents a *data based low-order controller design* algorithm for a linear time-invariant process with a time delay. The algorithm is composed by combining an identification step based on open loop pulse test with a low-order controller design step to obtain the entire set of controllers achieving multiple performance specifications. The initial information necessary for this algorithm are merely the width and amplitude of a rectangular pulse, a controller of four types (PI, PD, PID, first-order), and design objectives. Various parametric approaches that have been developed are merged in the controller design algorithm. The resulting controller set satisfying the design objectives are displayed on the 2D and 3D graphics and thus it is very easy for us to pick a controller inside the admissible set because we can check the corresponding closed-loop performances visually.

**Key Words** : Data based controller design, Three parameter controller, Moment matching, PID, first-order controller, Autotuning algorithm

### 1. Introduction

In industrial process control systems, it was reported in [1] that more than 90% of the control loop are of PID type. The Ziegler & Nichols rules have been famous for over sixty years and Astrom and Hagglund relay experiment has been around for twenty years. Over the decays, PID control technology has undergone many changes. The design approaches can be classified with two categories, depending on the quality and type of the process model information used, and whether or not optimization concepts have been used to generate the PID controller tuning [2].

In *model-free methods* [3, 4], the explicit identification of significant model points or a parametric model is not used. Whereas a local modeling is continuously updated via the knowledge of the input-output behavior. In [5, 6], it was shown that the complete set of stabilizing PID and first-order controllers for a linear time-invariant (LTI) plant with time delay could be calculated directly from the frequency response data. *Nonparametric model based design* uses the explicit identification of significant modelpoints but doest not use a parametric model. These approaches basically rely on the relay experiment due to Astrom and Hagglund [1, 7]. *Parametric model based method* depends on the use of a transfer function model. Despite many good design methods, practical control engineers feel more attractive to automatic tuning of PID controller because they do not like to tune a loop over a long period of time. Autotuners of major vender include identification methods using mainly step, ramp, pseudo-random binary sequence (PRBS), and relay feedback tests [8]. On the other hand, an important breakthrough on PID controllers was reported in [9]. This approach as well as a number of recent results have been described in [10]. These methods can provide the complete set of stabilizing PID and first-order controllers for a LTI plant model with a delay. The computations involved in most of these methods are mainly linear programings and linear equations. It is important to note that all these solutions can be displayed on 2D and 3D graphics in parameter space because PID and first-order controllers have at most three parameters. This set can be used for the first step to enable the design of systems achieving multiple performance specifications by intersections of each set. In [11, 12], the *characteristic ratio assignment* (CRA) method to deal with the fixed-order controller design problem under time response specifications was proposed. By combining the CRA with the results of Bhatacharyya et al. in [10], a *three parameter control design* (TPCD) algorithm [13] has been developed. It can be used for designing a three parameter controller achieving multiple design objectives: the entire set of controllers satisfying the given stability margins and a set of controllers satisfying the prescribed limits

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of overshoot and settling time.

The purpose of this paper is to present a *data based low-order controller design* (DBLCD) algorithm for a LTI plant with a time delay. This algorithm consists of an identification and a controller design steps. By *data based*, we mean that the proposed algorithm does not require one to make an identification for the process except giving some initial data for a test input. For this purpose, we have developed a simple identification method for continuous-time low-order models such as a first-order plus time delay (FOTD) or a second-order plus time delay (SOTD) models from the open-loop pulse test. Wherein the identification of the process parameters can be determined by a closed form formula. The formula requires only a few moments of a rectangular pulse response. This moment matching method have been extended to the identification of different low-order models [14]. It was shown that the identification method has not only good accuracy to noisy data but also provides a robust approximation of high-order process. In particular, since the test input is just a single rectangular pulse, it can be easily applied to the actual process and returns to the original state in a very short period of time. Thus, this is very suitable to the DBLCD.

By *low-order controller design*, we here mean that for an identified process model, (i) low-order controllers to be considered are restricted within four types of controllers (PI, PD, PID, first-order), (ii) the complete set of controllers of the selected type achieving stability is determined, (iii) the complete set of controllers of the selected type achieving the prescribed gain and/or phase margins is determined, (iv) a set of controllers of the selected type satisfying the prescribed transient response specifications: overshoot and settling time is obtained, and (v) several design objectives above can be intersected to simultaneously satisfy. In this DBLCD, the *low-order controller design* is carried out by using the TPCD algorithm, that we have developed previously in [13].

The main contribution of this paper is to present a DBLCD algorithm, as will be described in Section 2.2 and 2.4, that allows us to obtain a set of low-order controllers satisfying the multiple objectives. The identification method in Section 2.3 has been originally developed for this DBLCD. After extending this approach to different models, all the details including these cases have been reported in [14]. The DBLCD algorithm begins with acquiring a pulse response data and provides the outcomes although we are not required to fulfil any processes for identification and synthesis directly. So, this algorithm can be easily used for autotuners of PID and first-order controllers as well as a design toolbox.

The organization of paper is as follows. In Section 2, we first give a feature of the DBLCD to be developed and propose an architecture of the data based design method. In Section 2.3, we explain a novel identification method based on the moments of pulse response data. Then a low-order controller design method, the TPCD algorithm will be followed. In Section 3, we give an illustrative example to show the effectiveness of the DBLCD.

## 2. Data Based Low-Order Controller Design

### 2.1 A feature of DBLCD

We first state the main problem concerned with a data based controller design for a linear time-invariant(LTI) system.

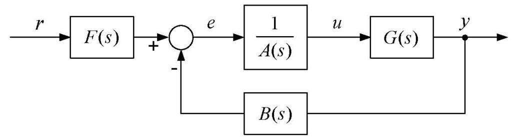



Fig. 1 A two-parameter feedback control system.

A feature of the data based low-order controller design is as follows:

i) A plant model $G(s)$ is not known but the test input and the response data are available.

ii) The controller structure is a two-parameter configuration shown in Fig. 1 and a controller is selected out of four types of controllers; PI, PD, PID, and first-order controllers.

iii) The resulting controller shall satisfy each or some of the following design objectives simultaneously;
  (a) closed-loop stability,
  (b) time response specifications, such as the maximum overshoot and settling time, and/or
  (c) stability margins such as gain and phase margins.

iv) The resulting sets of PI, PD, PID, and first-order controllers should be displayed on 2D and 3D graphics in controller parameter space, so that designers can select a controller parameter from the admissible set.

We assume that the plant to be considered is a LTI system without positive zeros. From this assumption, it is clear that the output to any positive input reacts positively. Furthermore, it is assumed that the plant is not so much complex and thus can be well approximated by two types of models: first-order plus time delay (FOTD) and second-order plus time delay (SOTD) models.

It is important to note that the data based design is different from the model-free design. The model-free control is based on an continuously updated local modeling via the unique knowledge of the input-output behavior[4]. Whereas the former requires to look for a model using the usual black box identification, which is valid within an operating range. Thus, it is necessary to include an identification process implicitly in this approach.

## 2.2 Architecture of the data based design method

As a way for solving the problem above, we propose an architecture of auto-tuning algorithm shown in Fig. 2. This algorithm consists of three processes: 1) data acquisition from an open-loop pulse test, 2) identification of low-order process model, and 3) determining a set of controllers of the selected type (PID and first-order) achieving the multiple design objectives.

If we enters only several information for the width and amplitude of a input pulse, controller type, and design specifications mentioned in previous section, the proposed autotuning algorithm provides the solution to the controller parameters on the 2D and 3D graphics.

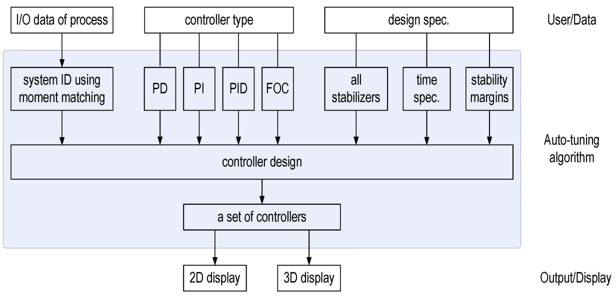



Fig. 2 Block diagram of data-based low-order controller design algorithm.

In the data acquisition step, a single rectangular pulse input for testing is applied to a plant and then the corresponding response data are collected. The second step is the identification process. As selected by designer, one of the FOTD and SOTD models is identified by means of the closed form formula using only moments of the acquired output data. Only if we calculate a few moments from the pulse response data, the parameters of the model can be determined by using the recent result [14]. In particular, it is pointed up that this identification method is very suitable for autotuning algorithm because the testing input is very simple and can be easily applied to any actual systems, and moreover it takes very short period of time compared with a step input test. In spite of a simple testing input, it was shown in [14] that this identification yields high accuracy and is very robust against noise and order mismatching as well.

The third process is to determine the entire set of all stabilizing three parameter controllers, the entire set of controllers with guaranteed stability margins, and a set controllers satisfying the desired transient response. The resulting set of controller parameters will be provided on the 2D and 3D graphics, so that one can choose a controller inside the admissible set. Let the design specifications be $\phi_i$, for $i=1,2,3$, where $\phi_1$, $\phi_2$, and $\phi_3$ indicate stabilizers, time response specifications, and stability margins. In the third stage, we can obtain a set of low-order controllers satisfying various design specifications, for instance, $S:=S_{\phi_1}\cap S_{\phi_2}$ or $S:=S_{\phi_1}\cap S_{\phi_3}$ or $S:=S_{\phi_1}\cap S_{\phi_2}\cap S_{\phi_3}$. For the purpose of doing this process, We will combine the so called three parameter controller design (TPCD) algorithm [13] with the above identification process. The main algorithms in the TPCD are composed by integrating several methods [9, 10, 11, 12, 17].

Now we will represent how to obtain two types of process models in detail and a brief summary of the TPCD in next two sections.

## 2.3 A novel method for identification of FOTD and SOTD models from pulse response data

It is very common that most of dynamics of industrial processes can be characterized by FOTD and SOTD models. In [15, 16], it was reported that a high-order LTI system can be well approximated by a low-order model provided that the first N moments of both models are equal.

The $i^{th}$ moment of a real-valued function $f(x)$ is defined as

$$m_i := \int_0^\infty x^i f(x)\,dx, \quad \text{for } i=0,1,2,\cdots \tag{1}$$

Note that the zero moment of $f(x)$, $m_0$, is equal to its area.

For a LTI process model with a single input $u(t)$ and a single output $y(t)$, the moments are written by

$$m_i^u := \int_0^\infty t^i u(t)\,dt,\ m_i^y := \int_0^\infty t^i y(t)\,dt. \tag{2}$$

Let the $i^{th}$ moment of the impulse response of a model $G(S)$ be $m_i^g$. Then Moments of the impulse response of a LTI process model can be represented in terms of moments of its input and output in a recursive manner [14].

$$m_k^g = \frac{1}{m_0^u}\left[m_k^y - \sum_{i=0}^{k}\binom{k}{i} m_{k-i}^g m_i^u\right], \quad \text{for } i=0,1,2,\cdots \tag{3}$$

where $\binom{k}{i}=\frac{k!}{i!(k-i)!}$ is the binominal coefficient and $m_0^g=\frac{m_0^y}{m_0^u}$.

We now consider the identification problems of low-order models based on moments matching. The

FOTD and SOTD models are described as

$$\text{FOTD: } G_1(s)=\frac{K}{Ts+1}e^{-Ls}, \tag{4}$$

$$\text{SOTD: } G_2(s)=\frac{K\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}e^{-Ls}, \tag{5}$$

where $K\neq 0$, $T>0$, $L\geq 0$, $\zeta\geq 0$, $\omega_n>0$. Here, $K$, $T$, $L$, $\zeta$, and $\omega_n$ represent the process gain, time constant, time-delay, damping ratio and natural frequency, respectively.

We introduce a single rectangular pulse input as follows:

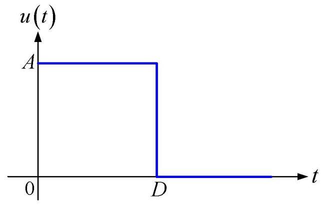



Fig. 3 A single rectangular pulse.

From (2), the $k^{th}$ moments of $u(t)$ are obtained by

$$m_k^u=\frac{1}{k+1}AD^{k+1},\ \text{ for } i=0,1,2,\cdots \tag{6}$$

Typical responses of the processes (4) and (5) to a finite pulse input are shown in Figs. 4 and 5.

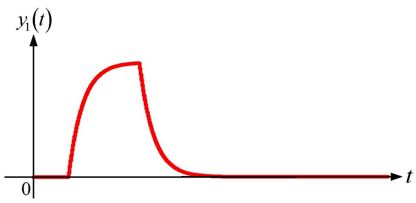



Fig. 4 A pulse response of FOTD system.


Fig. 5 A pulse response of SOTD system.

Let the $k^{th}$ moments of a rectangular pulse response be $m_k^y$. Then the parameters of FOTD and SOTD models can be determined explicitly by calculating only a few moments of output, since the input moments are known a priori. More results in detail are referred to [14].

Proposition 1 Suppose that there exists a FOTD model such that $G_1(s)=G(s)$. A FOTD model in (4) can be determined by

**Proposition 1** *Suppose that there exists a FOTD model such that $G_1(s)=G(s)$. A FOTD model in (7) can be determined by*

$$\text{(i) } \hat{K}=\frac{m_0^y}{AD}, \tag{7}$$

$$\text{(ii) } \hat{T}=\sqrt{\frac{m_2^y}{m_0^y}-\left(\frac{m_1^y}{m_0^y}\right)^2-\frac{1}{12}D^2}, \tag{8}$$

$$\text{(iii) } \hat{L}=\frac{m_1^y}{m_0^y}-\frac{1}{2}D-\hat{T} \tag{9}$$

*where the hat "ˆ" indicates the estimated value.* ♣

**Proposition 2** *Suppose that there exists a SOTD model such that $G_2(s)=G(s)$. A SOTD model in (8) can be determined by*

$$\text{(i) } \hat{K}=\frac{m_0^y}{AD}, \tag{10}$$

$$\text{(ii) } \hat{L}=c_1-\theta_1^*. \tag{11}$$

$$\text{(iii) } \widehat{\omega_n}=\sqrt{\frac{2}{(\theta_1^*)^2+c_1^2-c_2}}, \tag{12}$$

$$\text{(iv) } \hat{\zeta}=\frac{1}{2}\widehat{\omega_n}\theta_1^* \tag{13}$$

*where $\theta_1^*$ is a real positive solution to the cubic equation,*

$$\theta_1^3+3(c_1^2-c_2)\theta_1+(2c_1^3-3c_1c_2+c_3)=0, \tag{14}$$

*and*

$$c_1=\frac{m_1^y}{m_0^y}-\frac{m_1^u}{m_0^u},$$

$$c_2=\frac{m_2^y}{m_0^y}-2\frac{m_1^u}{m_0^u}\left(\frac{m_1^y}{m_0^y}-\frac{m_1^u}{m_0^u}\right)-\frac{m_2^u}{m_0^u},$$

$$c_3=\frac{m_3^y}{m_0^y}-3\frac{m_1^u}{m_0^u}\frac{m_2^y}{m_0^y}-\left(3\frac{m_1^y}{m_0^y}-6\frac{m_1^u}{m_0^u}\right)\frac{m_2^u}{m_0^u}-6\left(\frac{m_1^u}{m_0^u}\right)^2\left(\frac{m_1^y}{m_0^y}-\frac{m_1^u}{m_0^u}\right)-\frac{m_3^u}{m_0^u}.$$

♣

In Proposition 2, the parameters $c_1$, $c_2$, and $c_3$ are known constants since they can be calculated by means of the moments of input and output using (3).

Moments are computed by the numerical sum through the use of acquired experimental data as follows.

$$\widehat{m_i^u}:=\sum_{k=1}^{N_T}t^i u(k\Delta t),\ \widehat{m_i^y}:=\sum_{k=1}^{N_T}t^i y(k\Delta t),\quad \text{for } i=0,1,2,3.. \tag{15}$$

where $N_T$ and $\Delta t$ denote the number of data points and the step size, respectively. A guide for selecting a proper input pulse and step size is referred to [14].

To sum up, after collecting the input and output data from a pulse test, we calculate a few moments of output using (15) and then the parameters of the FOTD and SOTD models are determined by using the Propositions I and 2, respectively.

### 2.4 Low-order controller design using the TPCD algorithm

Through the identification in previous step, we now have a process model which is either FOTD or SOTD model. This model is entered into the low-order controller design step. The three parameter control design algorithm, TPCD, provides a set of controllers that meet the prescribed specifications. The TPCD algorithm [13] allows us to select one of four types of controllers (PI, PD, PID, and first-order). The structure of controller has been considered by two-parameter configuration shown in Fig. 1. These controllers are equivalent to the following forms:

PI: $A(s)=s,\ B(s)=k_p s+k_i$ (16)

PD: $A(s)=1,\ B(s)=k_d s+k_p,$ (17)

PID: $A(s)=s,\ B(s)=k_d s^2+k_p s+k_i,$ (18)

First-order controller : $A(s)=s+x_3,\ B(s)=x_1 s+x_2.$ (19)

In practice, this control structure can be implemented by transforming into an observer canonical form. Also, the feed-forward gain, $F(s)$, is determined so that the DC gain of the overall transfer function is equal to unity.

There are three categories of design specifications wherein we choose one or multiple objectives: 1) the complete set of controllers of the selected type achieving stability, 2) the complete set of controllers of the selected type achieving the given stability margins, and 3) a set of controllers satisfying the desired transient responses such as overshoot and settling time. It is important to note that unlike conventional optimization approaches that seek a single best controller, the above methods seek the entire set of controllers satisfying stability margins as well as absolute stability and also find a set of controllers satisfying time response specifications.

Main algorithms used in the TPCD are as follows:

(a) S.P. Bhattacharyya et al. [9, 10] and references therein for the entire set of stabilizing PI, PD, PID, and first-order controllers,

(b) S.P. Bhattacharyya et al. [10] and references therein, and Kim [17] for the complete set of PI, PD, PID, and first-order controllers with guaranteed gain and phase margins,

(c) Kim et al. [12, 13] for a set of PI, PD, PID, and first-order controllers that meets the specified maximum overshoot and settling time.

All the results obtained are displayed on 2D and 3D graphics in controller parameter space. This is an important advantage of dealing with three term controllers. More details for TPCD are referred to [13]. Finally, we can choose a controller from the resulting sets of controllers by just clicking on the 2D and 3D graphics.

## 2.5 Algorithm for data based low-order controller design

The data based design flow of three term controllers is shown in Fig. 6. The algorithm is given as follows:

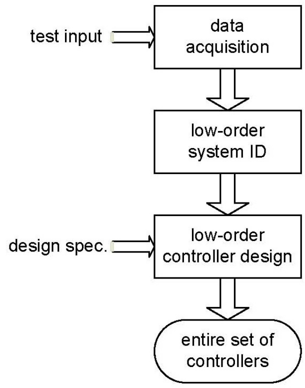



Fig. 6 Design flow of the auto-tuning procedure.

**The DBLCD algorithm:**

**Step 1**: Select a controller out of four types: PI, PD, PID, and first-order controllers. Assume that the controller be of two-parameter configuration and then it is implemented by an observer canonical form.

Choose one of three design objectives; the complete set of all stabilizing controllers, the complete set of all controllers with stability margins, a set of controllers satisfying the desired time response.

Select proper duration($D$) and amplitude($A$) of the pulse as an open-loop test input and the step size($\Delta t$) for sampled data.

**Step 2**: Apply the test input to the process and collect the response data until the output returns to the original state.

Check whether the output has negative response before going to the peak value. If it is so, the plant is not a minimum phase system. In that case, the identification based on the method of moments may be not so good.

**Step 3**: Calculate the first three moments (that is, from zero to third moments) of output using (15) and the acquired data.

**Step 4**: Determine the parameters of FOTD (or SOTD) by using the Proposition 1 (or Proposition 2).

**Step 5**: Run the TPCD algorithm with the identified model in the Step 4 under controller type and design objectives given in Step 1. Then we have the solution for a three parameter controller in 3D graphic.

**Step 6**: One can find a PID gain ($k_p, k_i, k_d$ ) from the 3D solution. Picking a point in the admissible ($k_d-k_i$) set with a fixed $k_p$, then various closed-loop performances are displayed so that we can confirm whether the other specifications are satisfactory. Similarly, we can pick a first-order controller gain ($x_1, x_2, x_3$) from the 3D solution.

## 3. An Illustrative Example

In this section, we give an illustrative example to show the data-based low-order controller design approach.

Instead of an actual process, we consider the following high-order process;

$$G(s)=\frac{(8s+1)(4s+1)}{(10s+1)^2(5s+1)(2s+1)^2(s+1)} \qquad (20)$$

Suppose that we want to find the complete set of both PID and first-order controllers that guarantees the gain margin (GM) of 6 [dB] and the phase margin (PM) of 45 [degree] for the process.

When a rectangular pulse with $A=1$ and $D=11$ is applied to this process, the output associated with white Gaussian noise of $SNR=20$ is shown in Fig. 7.

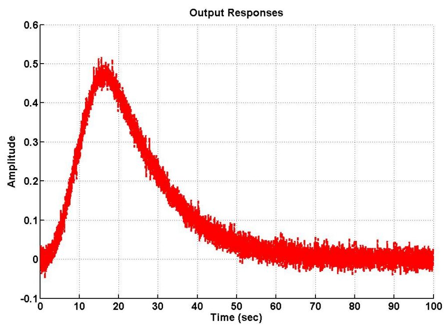



Fig. 7 Process output.

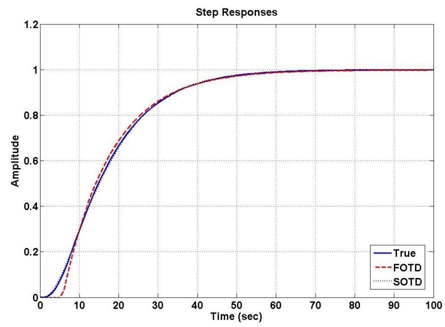


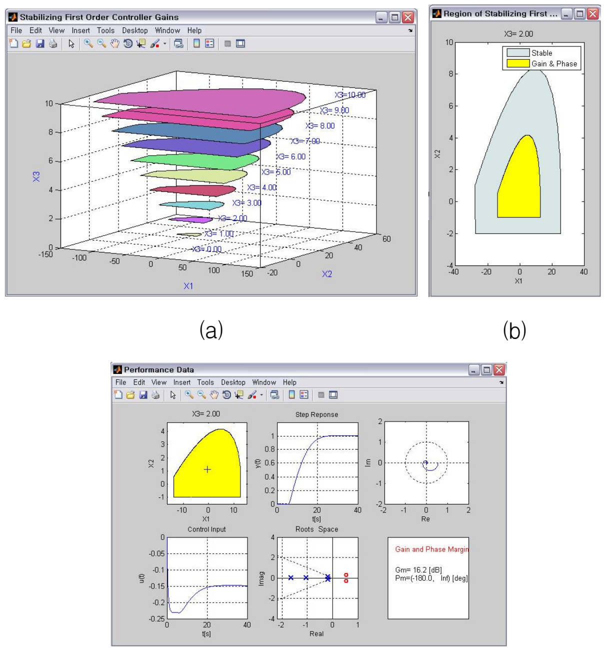

Fig. 9 Step responses of the actual process and identified models

For the numerical calculation of moments, the number of data and the step size used are $N_T=10000$ and $\Delta t=0.01$[sec], respectively. The identified FOTD and SOTD models result in

$$\widehat{G}_1(s)=\frac{0.9993}{12.27s+1}e^{-5.67s}, \qquad (21)$$

$$\widehat{G}_2(s)=\frac{0.9993}{66.69s^2+16.85s+1}e^{-1.09s}. \qquad (22)$$

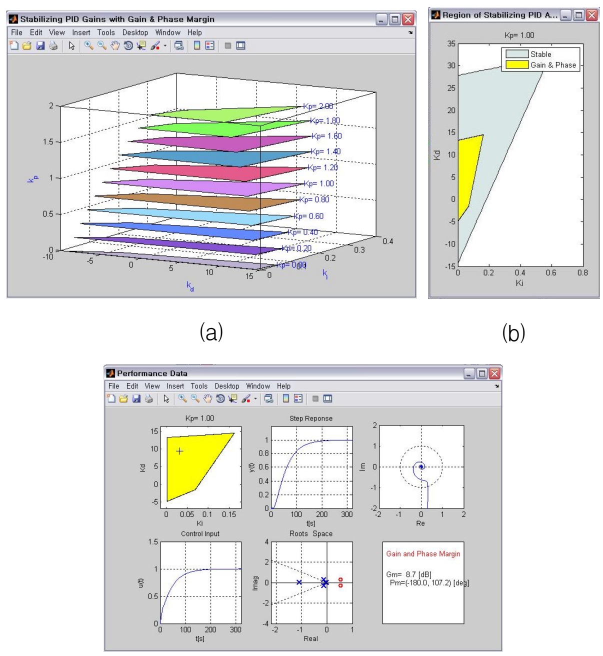
The step responses of (20)-(22) are shown in Fig. 8. It is seen that the step response of identified SOTD model is almost coincided with that of the actual process. Here we use the FOTD model for first-order controller design while the SOTD for PID controller for the purpose of illustration. We enter the design information, for example, GM and PM, controller type into the TPCD. The resulting set of first-order controllers with guaranteed GM and PM, $S_{GM}\cap S_{PM}$, are shown in Fig. 9(a). The entire set of all stabilizing PID controllers is given in Fig. 10(a). The TPCD allows us to pick a $x_3$ among the




(a) (b)

(c)

Fig. 9 The resulting set of first-order controllers with guaranteed stability margins.




(a) (b)

(c)

Fig. 10 The resulting set of PID controllers with guaranteed stability margins.

set $S_{GM} \cap S_{PM}$. Fig. 9(b) shows the entire region of stabilizing first-order controllers in the $x_1 - x_2$ plane when $x_3 = 2.0$. Therein, if we pick a pair of $(x_1, x_2)$ by clicking, the corresponding performances data, step response, control input profile, closed-loop pole locations, and nyquist plot are displayed in another window, as shown in Fig. 9(c). It is possible to check visually which points of the set $S_{GM} \cap S_{PM}$ yield satisfactory performances. This is very important advantage. The similar cases for PID design are shown in Figs. 10(b) and (c).

## 5. Concluding Remarks

In this paper, a new algorithm for data based low-order controller design was presented. In this framework, two types of process models, FOTD and SOTD models are identified by a new novel identification method using moment matching. The test input is solely a single rectangular pulse and the parameters of identified low-order models are determined by computing a few moments of output. Thus it can be easily applied to any actual processes and is suitable for the DBLCD. For this identified process model, the entire set of low-order controllers simultaneously satisfying multiple design specifications is determined by using Matlab based TPCD algorithm. The resulting controllers are displayed on the 2D and 3D graphics so as to pick a controller inside the admissible set.

The DBLCD algorithm begins with acquiring a pulse response data and provides the outcomes although we are not required to fulfil any processes for identification and synthesis directly. So, this algorithm can be easily used for an autotuner of PID and first-order controllers as well as a design toolbox. It is also anticipated that the proposed DBLCD algorithm will be very useful for practical engineers.

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