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A Model Identification Method for Tuning of PID Controller in a Smith Predictor Structure

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Abstract: In this paper, a model identification method is presented for tuning of PID parameters in Smith predictor structure based on internal model control. The purposed method fits stability boundary locus (SBL) of a plant model with SBL of a FOPDT (First Order Plus Dead Time) or a SOPDT (Second Order Plus Dead Time) model to determine the controller parameters. Two examples are employed to illustrate the applicability and simplicity of the purposed method in both tuning of controller parameters and identification of model parameters for an integer order plant and a fractional order plant.

Keywords: Model identification, stability boundary locus fitting, Smith predictor.

1. INTRODUCTION

Processes with time delay are commonly encountered in industrial systems (Åström & Hägglund, 2001). Using PID controllers in these processes leads to long settling time in time responses of systems. Although increasing of proportional gain k_p yields faster settling time, some limitations as overshoot and increasing tendency to instability appear in time response of the processes (Ingimundarson & Hägglund, 2001). Thus, various control strategies are introduced to achieve better control performance for such processes (Kaya, 2004; Normey-Rico & Camacho, 2008).

Smith Predictor control structure drawn in Fig. 1 is commonly preferred to use in processes with time delay (Kaya, 2004). This structure consists of a plant with time delay, a model with time delay and a PID controller. FOPDT and SOPDT models are used in the structure for tuning the controller parameters. Performance of the Smith predictor is dependent on matching between characteristic of these models and characteristic of the plant transfer function (Zhang & Xu, 2001). Some important methods were developed to calculate the model parameters and determine the controller parameters (Benouarets, 1994; Kaya & Atherton, 2001; Kaya, 2004; Palmor & Blau, 1994).

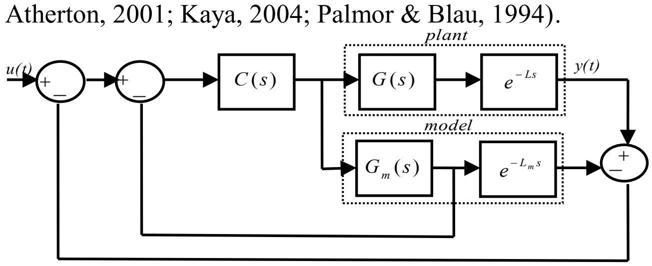

Fig. 1. Smith predictor structure.

In this study, stability boundary locus (SBL) fitting method is applied to calculate the model parameters in Smith predictor configuration and obtain PID controller parameters by using internal model control (IMC) strategy.

SBL method is typically used for stability analysis and defining stability regions for closed loop control systems with PI/PID controllers in literature (Tan et al., 2006; Tan, 2005). Briefly, SBL defines a curve which separates stable and unstable regions in (k_p, k_i) plane and stability region indicates all controller parameters which provide stabilization for a closed loop control system. In a previous study, SBL method was performed for stabilization analysis of Smith predictor and identification parameters of models based on selected controller parameters in stability region of Smith predictor represented by IMC (Deniz et al.,2015). Then, SBL fitting method was used for model reduction to design a PID controller (Deniz et al., 2015). Recently, an integer order approximation method based on SBL fitting has been presented for fractional order derivative and integrator operators (Deniz et al., 2016).

In present study, the aim of SBL fitting method is to match SBL of plant transfer function to SBL of a FOPDT or SOPDT model in the closed loop control system. Therefore, the SBL of plant transfer function is calculated in a closed loop control system with a PI controller. Then, the plant transfer function is replaced with the model transfer function with unknown coefficients to fit the SBL. Characteristic equation formed by using unknown coefficients of model yields a system of linear equations. The unknown coefficients of the model are found by solving the linear equations for the sampling points selected from the SBL of the plant transfer function. Selection of time delay parameter is also based on minimization of SBL fitting and step response errors. The main contribution of this study is to use SBL fitting approach for estimating the approximate model of real system. This technique provides better fitting of the characteristic equations of the closed loop system with estimated model and actual system under PI control.

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This paper is organized as follows: Section 2 describes stability boundary locus (SBL) method and gives a procedure for calculation of the parameters of FOPDT and SOPDT models using SBL fitting method. Section 3 presents a PI/PID controller tuning strategy for Smith predictor structures based on internal model control. Illustrative examples are presented in Section 4. Concluding remarks are given in Section 5.

2. MODEL IDENTIFICATION METHOD

2.1 Stability Boundary Locus Method

Consider a PI controller given by $C(s) = k_p + \frac{k_i}{s}$ and a plant transfer function with time delay given by $G(s) = \frac{N(s)}{D(s)} e^{-Ls}$ in a feedback system; one can determine the characteristic equation of this system as follows,

$$\begin{aligned} \Delta(s) &= 1 + C(s)G(s) \\ &= sD(s) + (k_p s + k_i)N(s)e^{-Ls} \\ &= 0 \end{aligned} \tag{1}$$

By substituting $s = j\omega$ and solving characteristic equation according to equating real and imaginary parts of $\Delta(j\omega)$ to zero, the following equations are obtained:

$$\begin{aligned} &k_i(N_R(\omega)\cos(\omega L) + N_I(\omega)\sin(\omega L)) + \\ &k_p(-\omega N_I(\omega)\cos(\omega L) + \omega N_R(\omega)\sin(\omega L)) = \omega D_I(\omega) \end{aligned} \tag{2}$$

$$\begin{aligned} &k_i(N_I(\omega)\cos(\omega L) + N_R(\omega)\sin(\omega L)) + \\ &k_p(\omega N_R(\omega)\cos(\omega L) + \omega N_I(\omega)\sin(\omega L)) = -\omega D_R(\omega) \end{aligned} \tag{3}$$

where, $N_R(\omega)$ and $N_I(\omega)$ are real and imaginary parts of the numerator polynomial. Similarly, the polynomials $D_R(\omega)$ and $D_I(\omega)$ are real and imaginary parts of denominator polynomial. $k_p(\omega)$ and $k_i(\omega)$ are determined from (2) and (3) as follows,

$$k_p(\omega) = -\frac{\begin{aligned}&[(N_I(\omega)D_I(\omega) + N_R(\omega)D_R(\omega))\cos(\omega L) + \\ &(N_I(\omega)D_R(\omega) - N_R(\omega)D_I(\omega))\sin(\omega L)]\end{aligned}}{N_I(\omega)^2 + N_R(\omega)^2} \tag{4}$$

$$k_i(\omega) = \frac{\begin{aligned}&[(\omega N_R(\omega)D_I(\omega) - \omega N_I(\omega)D_R(\omega))\cos(\omega L) + \\ &(\omega N_R(\omega)D_R(\omega) + \omega N_I(\omega)D_I(\omega))\sin(\omega L)]\end{aligned}}{N_I(\omega)^2 + N_R(\omega)^2} \tag{5}$$

Using (4) and (5), SBL expressed by $S(k_p(\omega), k_i(\omega))$ and stability region, which indicates all stabilizing $k_p(\omega)$ and $k_i(\omega)$ values, can be obtained in (k_p, k_i) plane (Tan, 2005). Although, SBL is defined in the frequency range $\omega \in [0, \infty)$, stability region can be found in a finite frequency range such as $\omega \in [0, \omega_c]$, where ω_c is critical or last frequency.

2.2 Stability Boundary Locus Fitting for FOPDT and SOPDT Models

In this section, we summarize SBL fitting method to determine the parameters of FOPDT and SOPDT models.

After determining SBL of $G(s)$ as expressed in Section 2.1, one can obtain a system of linear equations for SBLs of FOPDT and SOPDT models with unknown coefficients. Then, sufficient numbers of sampling points from SBL of $G(s)$ are selected to solve these linear equations for good fitting.

Consider a FOPDT model transfer function given as

$$G_m(s) = \frac{K_m}{T_m s + 1} e^{-L_m s} \tag{6}$$

A PI controller with form of $C(s) = k_p + \frac{k_i}{s}$ and a FOPDT model transfer function $G_m(s) = \frac{a_0}{b_1 s + b_0} e^{-L_m s}$ are employed in a feedback system to obtain SBL of FOPDT model.

The characteristic equation of this system is

$$\begin{aligned} \Delta(s) &= 1 + G_m(s)C(s) \\ &= b_1 s^2 + b_0 s + (a_0 k_p s + a_0 k_i)e^{-L_m s} = 0 \end{aligned} \tag{7}$$

Using $s = j\omega$ and solving characteristic equation by considering real and imaginary parts equal zero, one can obtain the following equations

$$\omega a_0 k_p \sin(\omega L_m) + a_0 k_i \cos(\omega L_m) = \omega^2 b_1 \tag{8}$$

$$\omega a_0 k_p \cos(\omega L_m) - a_0 k_i \sin(\omega L_m) = -\omega b_0 \tag{9}$$

In order to calculate the parameters of FOPDT models depending on ω, k_p, k_i and L_m from (8) and (9), $b_0 = 1$ is considered for solution of homogeneous system of linear equations, and the unknown coefficients are determined as

$$a_0 = \omega b_0 /(-k_p \cos(\omega L_m) + k_i \sin(\omega L_m)) \tag{10}$$

$$b_1 = (\omega a_0 k_p \sin(\omega L_m) + a_0 k_i \cos(\omega L_m)) / \omega^2 \tag{11}$$

For finding values of a_0 by using (10), it is sufficient to select a SBL sampling point as $S(k_{p1}(\omega_1), k_{i1}(\omega_1))$ from SBL of $G(s)$ and an appropriate time delay, L_m. The last frequency value is preferred to be sampling point in a frequency range, $[\omega_{\min}, \omega_{\max}]$, where the stability region of $G(s)$ is located. Furthermore, selection of an appropriate time delay parameter is presented in following section.

Using value of a_0, (11) is solved for the same SBL sampling point to find values of b_1. Thus, the parameters of FOPDT model are determined as $K_m = a_0$ and $T_m = b_1$.

Parameters of SOPDT model are calculated when similar procedures are performed. Let take a SOPDT model transfer function as