A Study of Process Identification, Frequency Response Analysis and Optimum Proportional-Integral tunings for an Identified Temperature Control System

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ABSTRACT Single loop feedback control is commonly used in many industrial applications due to low cost. However, it still deserved an optimum control for the good performance of the controlled process to avoid failures and shutdown of the plants. A good control should have a proper process identification to imply the process dynamic behavior. This paper presents the process identification, frequency response analysis and an optimal PI tuning of a single loop controlled system without involving the complicated stage in determining the best PI tunings for both the servo and regulatory control problems at a nominal point. In realizing the objective, a temperature control function of the Process Control Simulator is chosen. Process identification of the First Order Plus Dead Time is obtained through the developed algorithm. Meanwhile, frequency analysis and the optimal PI tunings are studied by using MATLAB simulation tools. It is found that the produced responses are varied by adjusting the compensator ratio where the optimal PI tunings for a stable and aggressive control is eventually determined.

KEYWORDS: Single Loop Control; Process Identification; Frequency Analysis; MATLAB SISOTOOL; Optimal PI Tunings
I Received 29 April 2019 **II Revised** 16 May 2019 **II Accepted** 6 August 2019 **II Online** 28 August 2019 **II © Transactions on Science and Technology I**
Full Article

INTRODUCTION

Proportional, Integral and Derivative (*PID*) control is widely implemented in many industries (Astrom & Hagglund, 2001). Its systematic tuning approach was firstly introduced by Ziegler-Nichols (1942), where the frequency domain analysis was used for both open loop and closed-loop control systems. Thereafter, some tuning methodologies for instance Cohen-Coon (1953), Astrom and Hagglund (2001) and Marlin (1995) that calculated *PID* settings by directly imply the parameters and developed formulas of each method (Luyben & Luyben, 1997).

This paper presents the frequency response analysis using SISOTOOL function of MATALB in designing the Proportional-Integral (PI) settings for the Process Simulator, SE-201 (SOLTEQ, 2015). At first, Process model is identified. Routh-Hurwitz stability criterion is used to determine the setting limit of the tuned parameters and the Compensator (*C*) ratio is analyzed for obtaining controller's optimized PI settings. Then, the PI settings with different compensator values are applied to the Process Simulator where the best control performance can be determined.

Bode Diagram, Nyquist Diagram and Routh-Hurwitz Stability

Bode diagram reflects two quantitative measurements that determine the quality of performance known as Gain Margin (*GM*) and Phase Margin (*PM*) through measuring the Amplitude Ratio (A_r) and Phase Angle (Ø) versus the logarithm of frequency, ω (Ogata, 2010). *GM* is the difference between a amplitude value corresponding to Phase Crossover frequency (W_{pc}) angle of 180^0, which is reciprocal to A_r. The Bode plot clarifies the stability criterion by stating that a stable open-loop system would have *GM* > 1 or reciprocally $A_r < 1$. Upon the requirement, the closed-loop response is stable. An identical value for *GM* is approximated to 2.0 (Tavakoli & Fleming, 2003).

PM is the difference between a phase angle corresponding to when A_r is 1.0 and the phase angle of 180^0 (Marlin, 1995). When *PM* > 0, the system is stable, and when *PM* = 0, the system operates under sustained oscillations. The ω_{gc} is the frequency that correspond to $A_r = 1$. Typical system design would have phase margin of 30^0 to 60^0.

Apart of it, Nyquist diagram is another alternative medium to visualize the frequency response of a linear dynamic process in case of bode diagram is not applicable in the system that do not have open-loop stable dynamic process or non-monotonic phase slot. The Nyquist diagram presents the frequency response behavior of stable system with single curve of G-plane not to crossover the critical point of -1 (Luyben & Luyben, 1997).

Figure 1 illustrates block diagram of feedback control loop, comprises process and PI controller.

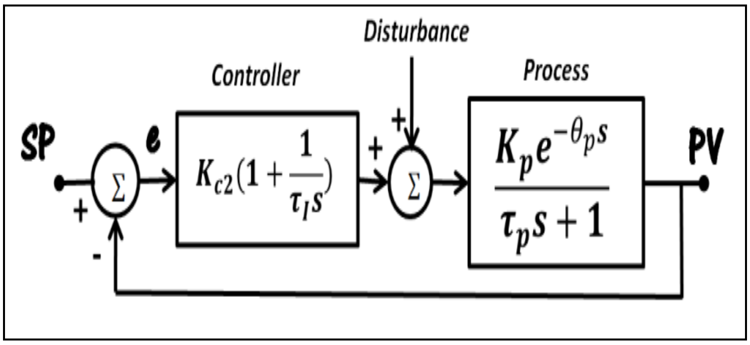


Figure 1. Block diagram of feedback control system.

Apply Taylor's approximation in stability analysis, solving of Characteristic Equation (CE) is shown in (1), which produces both upper and lower limits as in (2) and (3) :

$e^{\theta_p s} \approx (1 - 0.5\theta_p S)$

$$1+\left\{K_{c2}\left(1+\frac{1}{\tau_I s}\right)\right\}\left\{\frac{K_p(1-0.5\theta_p s)}{(\tau_p s+1)}\right\} = 0 \tag{1}$$

For term s^2, $(\tau_p \tau_I - \tau_I K_c K_p) > 0$

$$K_c < \frac{\tau_p}{K_p \theta_p} \quad \text{(upper limit)} \tag{2}$$

For s , $(\tau_I + \tau_I K_c K_p - K_c K_p \theta_p) > 0$

$$\tau_I > \frac{\theta_p K_c K_p}{1+K_c K_p} \quad \text{(Lower Limit)} \tag{3}$$

This paper proposes Compensator (*c*) ratio tuning in designing PI controller as shown in (4).

$$K_2 = c * \left[K_c\left(1+\frac{1}{\tau_I} s\right)\right] \tag{4}$$

Tan *et al.* (2008) explained SISOTOOL function in the MATLAB is able to tune *c* for generating graphical interactions of controlled system, which is displayed by the both Bode and Nyquist diagram.

First Order plus Deadtime Model Identification

Determining First Order plus Deadtime (*FOPDT*) is preliminary stages towards analysis of process dynamic for stable process control (Tavakoli & Fleming, 2003). The stages of determining *FOPDT* is presented in literature Chew *et al.* (2017).

Apart from it, it is also alternately obtained through the developed Graphical User Interface (*GUI*) that assists in calculating all the parameters to form the model. *GUI* basically is developed specifically in academic research where the research works conducts repetitive testing and exhausting manual calculations. Besides, *GUI* presents a consistent approach to produce process model when several input process data are provided. Moreover, *GUI* can deal with all excel spreadsheet that contains the data from the open loop test.

The developed *GUI* for the process model is illustrated in Figure 2.

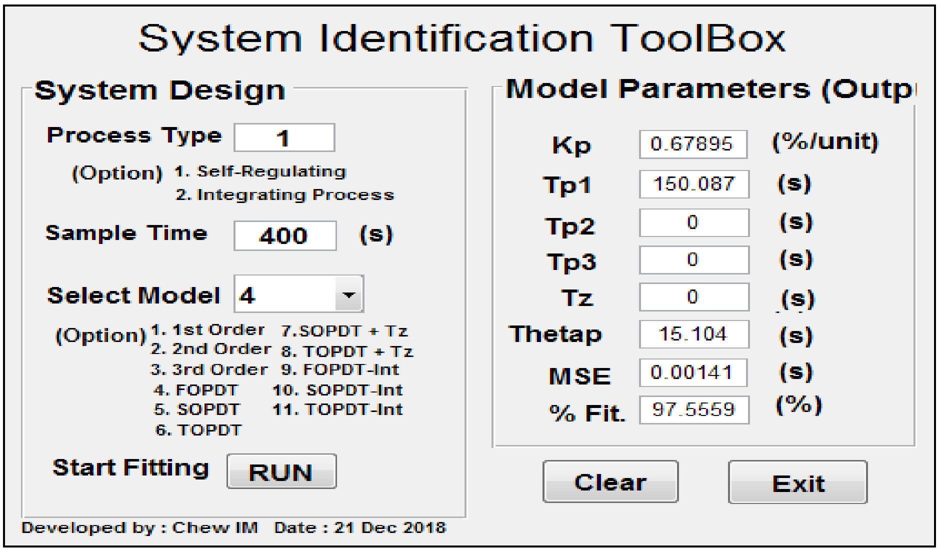


Figure 2. Process identification by using the developed System Identification Toolbox.

ANALYSIS AND RESULT

First Order Plus Dead Time and Closed Loop Stability

The process identification compared the real-time data with the predicted process model. The predicted FOPDT model in overall matched 97.6% as compared to real- time data (y1) as depicted in Figure 3. The corresponding *FOPDT* is developed as shown in (5):

$$G(s) = \frac{0.68e^{-15s}}{150s+1} \qquad (5)$$

Substituting, $\tau_p = 150$, $\theta_p = 15$ and $K_p = 0.68$ into (2),

$$K_c < 14.7 \quad \text{or} \quad \text{PB} > 6.8\%.$$

Refer to integral time constant, τ_I as in (3). Taking, $K_c = 14$ (<14.7), substitute, $\theta_p = 15$ and $K_p = 0.68$ gives

$$\tau_I > 13.57$$

Therefore, the applied tuning limits for PI controller are PB > 6.8% and $\tau_I > 13$.

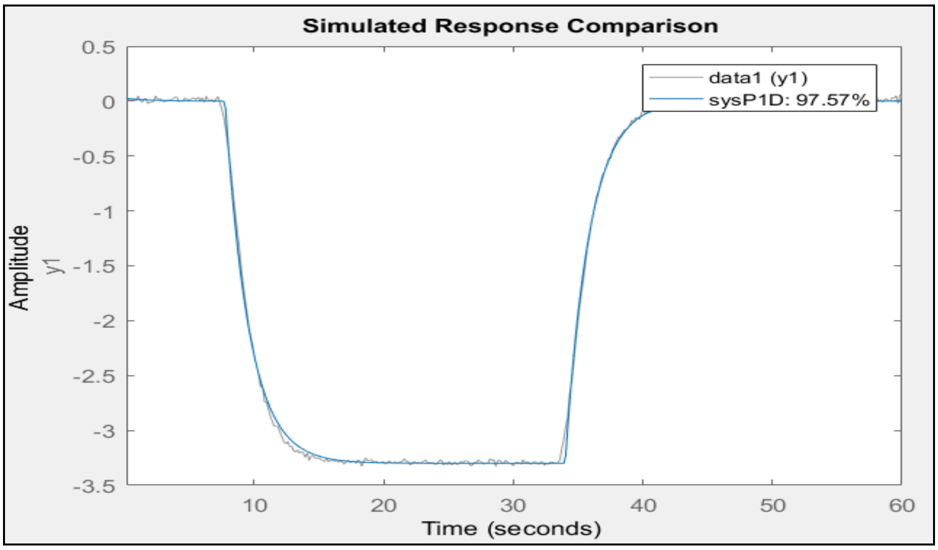
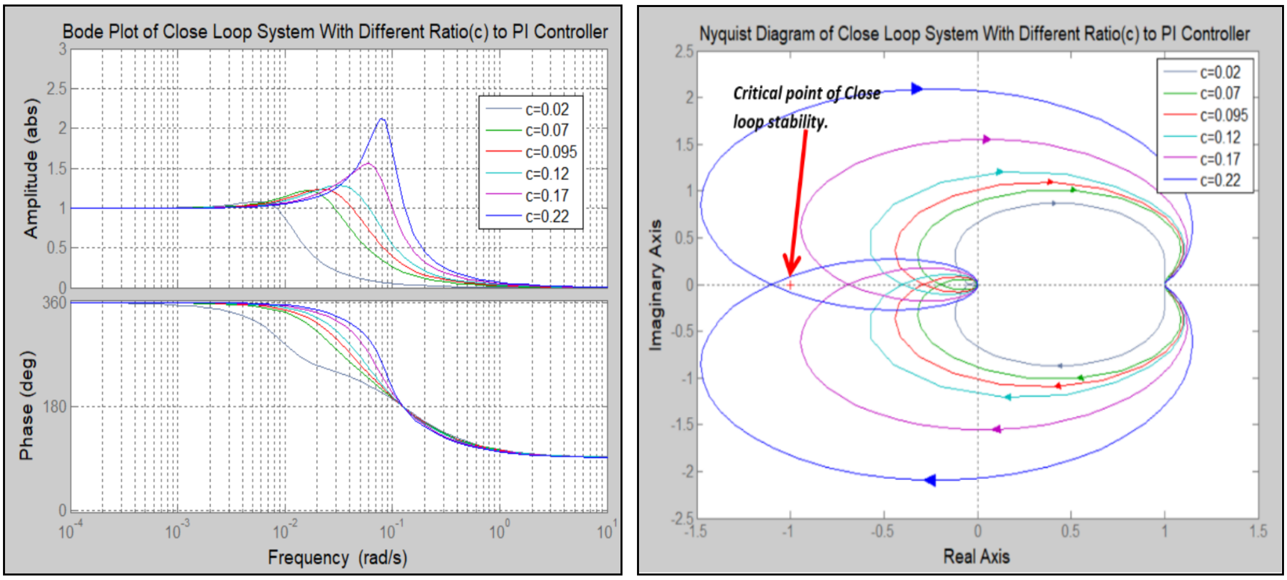


Figure 3. Predicted sysP1D versus real time data (y1).

Frequency Response and Tuning of Compensator, c

The view of Bode and Nyquist diagrams for the applied *c*s are shown by Figure 4 (a) and (b).



(a) (b)

Figure 4. Bode diagram of various compensator ratio, C

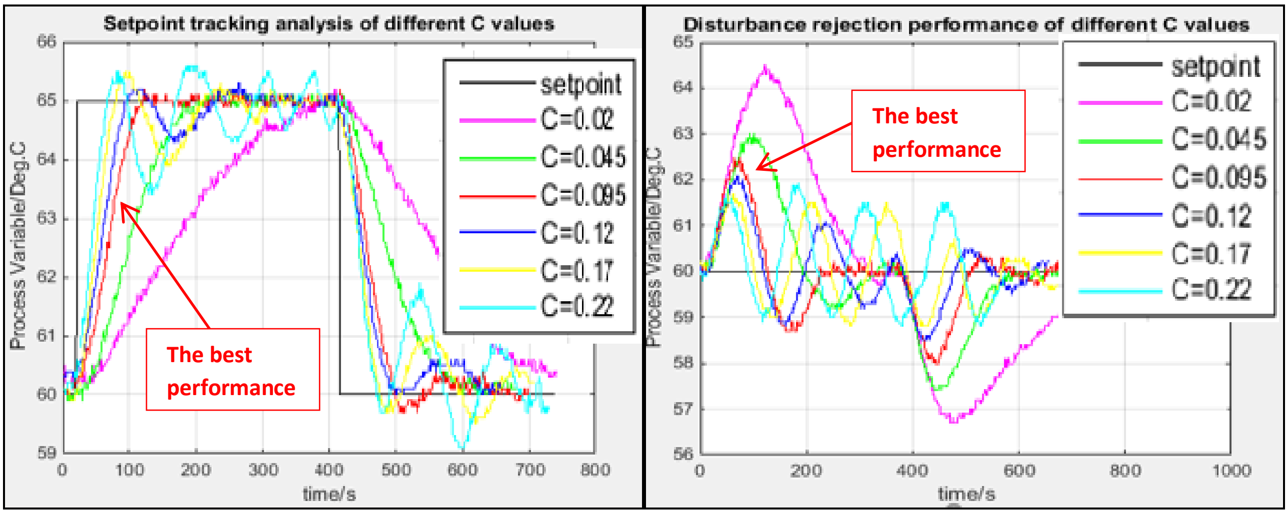
From the SISOTOOL function, acquisition of *GM* and *PM* from Figure 3 (a) and (b) were tabulated in Table 1. It was noted that the value of *GM* and *PM* are inversely related to *c* thereby increases aggressiveness of system response and ultimately causes controlled process to become unstable. It is also noted that the *c* tunings in SISOTOOL were tested till *c* = 0.22 and *PB* is approximated to 7%. Thereby, *c* tunings until 0.22 are used to obtain K_c and τ_I of PI controller.

Table 1. Gain Margin and Phase Margin

Compensat or ratio, *C*	Frequency Response			PI Controller Settings			
	GM	PM	Intersection Point	K_c	*PB* (%)	K_i	τ_i
c=0.02	23.205	120.025	(-0.0415 , 0)	1.13	88.5	0.0173	56.5
c=0.07	4.977	101.073	(-0.20, 0)	4.56	21.9	0.07	65
c=0.095	3.404	87.216	(-0.289,0)	6.19	16.2	0.095	65
c=0.12	2.487	65.897	(-0.395, 0)	7.82	12.8	0.12	65
c=0.17	1.461	23.364	(-0.680, 0)	11.1	9.0	0.17	65
c=0.22	0.902	-5.227	(-1.10, 0)	14.3	7.0	0.22	65

Relative Performance for Servo and Regulatory Control

Response of servo and regulatory controls are shown in Figure 5 (a) and (b).



(a) (b)

Figure 5. Servo and regulatory responses of various compensator ratios.

Table 2 depicts *c* = 0.12 till 0.22 that caused unstable response. The next consideration is *c* = 0.095, which is comparatively settling faster than other tunings. Thereby, it is selected as the optimal tuning for PI controller.

It is clearly denote that *c* = 0.095 is the best choice as the optimal tuning for the temperature control system of the Process Control Simulator-SE201, which gives the satisfactory response for both servo and regulatory control.

Table 2. Process Control Simulator SE-201 Performance for Servo and Regulatory Controls

Compensator	Servo Control		Regulatory Control	
	Rise Time (s)	Settling Time (s)	Overshoot (°C)	Settling Time (s)
c = 0.02	386	386	4.3	352
c = 0.045	203	203	2.9	315
c = 0.095	116	116	2.2	221
c = 0.12	94	197	2.0	unstable
c = 0.17	79	191	1.6	unstable
c = 0.22	67	unstable	1.5	unstable

CONCLUSIONS

Frequency response analysis provided the visualized performance of the control loop from the determined PI tunings based on the displayed figures in both Bode and Nyquist diagrams. Process Identification defined the dynamic behavior of the tested system. Applying the SISOTOOL function in MATLAB eliminated complex mathematic calculations in analyzing the response of varies PI controller settings for the operation of Process Control Simulator, SE-201. It is concluded that compensator ratio, c = 0.095 for the optimum tunings PI controller is PB = 16.2% and τ_i = 65s is the best ratio fixed to both servo and regulatory controls. The produced overshoots gave the fast setting time when compared to the other settings.

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