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A simple approach for on-line PI controller tuning using closed-loop setpoint responses

Mohammad Shamsuzzoha[a],*Sigurd Skogestad[a],Ivar J. Halvorsen[b]

[a]*Norwegian University of Science and Technology, Trondheim, Norway,*
*shamsuzz@chemeng.ntnu.no, *skoge@ntnu.no*
[b]*SINTEF ICT, Applied Cybernetics, N-7465 Trondheim, Norway,*

Abstract

A simple and new procedure has been developed for the PI controller tuning of an unidentified process using closed-loop responses. The method requires only one step test in the closed-loop system to obtain the proportional gain and integral time. The step test is a setpoint change performed with a proportional only controller while disabling any integral and derivative action. From the setpoint response one observes the overshoot and the corresponding time to reach the peak. In addition one observes the proportional gain (k_{c0}) and the steady-state offset. Based on a range of first-order with delay test processes, a simple analytical correlation has been developed for the controller gain (k_c/k_{c0}) as a function of the overshoot. The integral time setting is mainly a function of the time to reach the peak. The settings were derived to match the SIMC tuning rule (with τ_c=θ) which gives good robustness with a gain margin of about 3 and sensitivity peak (M_s-value) of about 1.6. The proposed tuning method, originally derived for first-order with delay processes, has been tested on a broad range of other stable and integrating processes. The results using the closed-loop data are comparable with the SIMC tuning rule using the open-loop model.

Keywords: PI controller, step test, closed-loop, SIMC

1. Introduction

The proportional integral (PI) controller is widely used in the process industries due to its simplicity, robustness and wide ranges of applicability in regulatory layer. Several papers have reported that a large number of PI controllers are poorly tuned and one reason is that quite tedious plant tests are needed for getting process parameters to finally obtain the appropriated controller setting. The classical method of Ziegler-Nichols [1] has the great advantages of requiring very little information about the process and testing under closed-loop conditions. However, it is well known that the Ziegler-Nichols [1] settings are aggressive for lag dominant (integrating) process and slow for delay dominant process. The other and more significant disadvantage of the Z-N method is that the system is brought at the limit to instability and that a number of trials may be needed to obtain the ultimate gain. An alternative is to induce sustained oscillation by using an on-off controller, i.e. relay tuning (Åström and Hägglund, [5]), but this is a bit difficult to use in practice because one needs to switch to an on/off-controller.

The original IMC-PID tuning method of Rivera et al. [2] and other related direct synthesis [3] methods provide very good performance for setpoint changes but give poor responses for input (load) disturbances in lag time dominant processes. To improve the input disturbance rejection, Skogestad [4] proposed the SIMC tuning rules where the integral time is reduced for lag-dominant (integrating) processes. The SIMC rule has one tuning parameter, the closed-loop time constant τ_c, and for "fast and robust" control is recommended to choose $\tau_c = \theta$, where θ is the effective time delay. The SIMC tuning rule requires that one first obtains a first-order plus delay model of the process, which involves approximations. Often, an open-loop experiment is used for getting the model parameters which may be time consuming and may upset the process and even lead to process runaway.

Therefore, there is need of an alternative closed-loop approach for plant testing and controller tuning which reduces the number of trails, avoids the instability concern during tuning experiment and works for a wide range of processes. The proposed new method satisfies these concerns:
1. The proposed method requires only a single experimental closed-loop test instead of a trial-and-error procedure under closed-loop condition.
2. The process is not forced to the stability limit, unlike Ziegler-Nichols [1] cycling method.
3. The method is applicable for both integrating and delay dominating process and gives satisfactory disturbance rejection performance.
4. The method is simpler in use than existing approaches and allows the process to be under closed-loop control.

2. SIMC tuning rules

A first-order process with time delay is a common representation of dynamics for process control and is given as:

$$g_p = \frac{ke^{-\theta s}}{\tau s + 1} \tag{1}$$

where k is the process gain, τ the dominant (lag) time constant and θ is the effective time delay. It is a fact that the majority of processes in the chemical industries can be satisfactorily controlled using a PI controller:

$$u(t) = k_c e(t) + \frac{k_c}{\tau_I}\int_0^t e(t)\,dt \tag{2}$$

which has two adjustable parameters, the proportional gain k_c and the integral time τ_I. The ratio $k_c/\tau_I = K_I$ is known as the integral gain.

The SIMC tuning rule (Skogestad, [4]) for the process (1) gives

$$k_c = \frac{\tau}{k(\tau_c + \theta)} \tag{3}$$

$$\tau_I = \min\{\tau, 4(\tau_c + \theta)\} \tag{4}$$

The SIMC tuning rule is analytically based and has found wide use in the industry. The closed-loop time constant (τ_c) is selected to give the desired trade-off between performance and robustness. This study is based on the "fast and robust" setting

$$\tau_c = \theta \tag{5}$$

which gives a good robustness with a gain margin of about 3 and sensitivity peak (M_s-value) of about 1.6. On dimensionless form, the SIMC tuning rules become

$$k_c' = k_c k = 0.5\frac{\tau}{\theta} \tag{6}$$

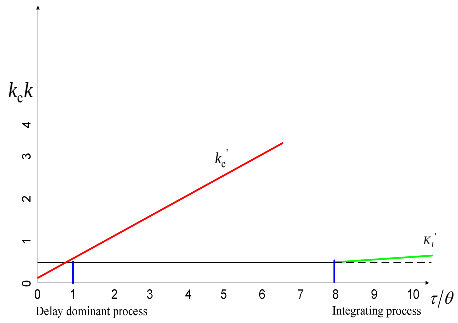
$$\tau_I/\theta = \min\left(\frac{\tau}{\theta}, 8\right) \tag{7}$$

Note that we have scaled time with respect to the delay θ which is approximately the same as the closed-loop time constant (with $\tau_c = \theta$). It is also of interest to consider the integral gain (K_I) on dimensionless form,

$$K_I' = \frac{k_c k}{\tau_I/\theta} = \min\left(0.5, \frac{1}{16}\cdot\frac{\tau}{\theta}\right)$$

The dimensionless gain k_c' and K_I' are plotted as a function of τ/θ in Figure 1.

3. Closed-loop experiment



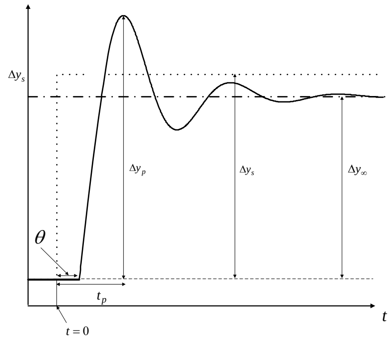


Figure 1. k_c and τ_I for SIMC tuning rule. Figure 2. Setpoint response with P-control

As mentioned, the objective is to use closed-loop data as basis for the controller tuning. For practical purpose, the simplest closed-loop experiment is a setpoint step response. Such a test is easy to make and one maintains full control of the process and the change in the output variable. We propose the following procedure;

1. Switch the controller to P-only mode (for example, increases the integral time τ_I to its maximum value or set K_I close to zero). In an industrial system, with bumpless transfer, the switch should not upset the process.
2. Make a setpoint change with an overshoot between 0.10 and 0.60 (about 0.30 is a good value) Most likely, unless the original controller was quite tightly tuned, one will need to adjust (increase) the controller gain to get a sufficiently large overshoot. From the closed-loop setpoint response, see Figure 2, record the following values

Δy_s : Setpoint change

Δy_p : Peak output change

t_p : Time from setpoint change to reach peak output

Δy_∞ : Steady-state output change after setpoint step test

k_{c0} : Controller gain used in experiment

From this data compute the following parameters

$$\text{Overshoot} = \frac{\Delta y_p - \Delta y_\infty}{\Delta y_\infty}, \quad b = \frac{\Delta y_\infty}{\Delta y_s}, \quad kk_{c0} = \frac{b}{1-b} \tag{8}$$

Note that a P-controller is used and (1-b) is the resulting relative steady-state offset The expression for the overall loop gain (kk_{c0}) is derived from the expression for the closed-loop transfer function, $b = kk_{c0}/(1+kk_{c0})$.

From Figure 1 we note that the integral term (K_I') is most important for delay dominant processes (τ/θ<1), but for other processes the proportional term k_c' is most significant. For close-to integrating process (τ/θ>8), the SIMC rule is to increase the integral term to avoid poor performance (slow settling) to disturbance at the plant input (''load disturbance''). These insights are useful for the next step when we want to derive tuning rules based on the closed-loop setpoint response.

4. Correlation between setpoint response and SIMC-settings

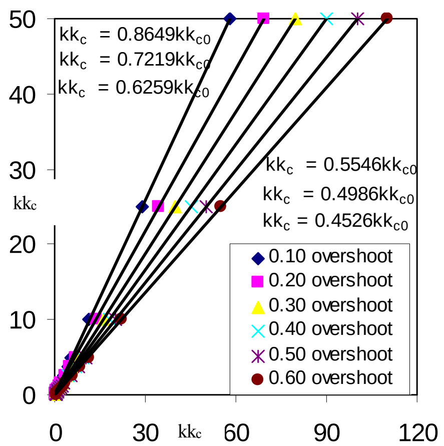
One could use the closed-loop setpoint response data to first determine the open-loop model parameters (k, τ, θ) and then use the SIMC-rules (or others) to derive PI-settings. A more direct approach is to directly compute from the data the PI-settings as proposed in this study. The goal is then to derive a correlation, preferably as simple as possible, between the setpoint response data (Figure 2) and the SIMC PI-settings in Eq. (3) and (4). For this purpose, we considered 15 first-order with delay models parameterized to cover a range of processes; from time delay dominant to lag-dominant (integrating).

τ/θ=0.1, 0.2, 0.4, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 5.0, 7.5, 10.0, 20.0, 50.0, 100.0

For each of the 15 process we obtained the value of k_c and τ_I using the SIMC-setting in Eq. (3) and (4) for τ_c=θ. Furthermore, for each of the 15 processes we generated 6 step setpoint responses (Figure 2) using P-controllers that give different fractional overshoots.

Overshoot= 0.10, 0.20, 0.30, 0.40, 0.50 and 0.60

In total we then have 90 setpoint responses. Note that small overshoots, less than 0.10, were not used. One reason is that it is difficult in practice to obtain from experimental data accurate values of the overshoot and peak time if the overshoot is too small.



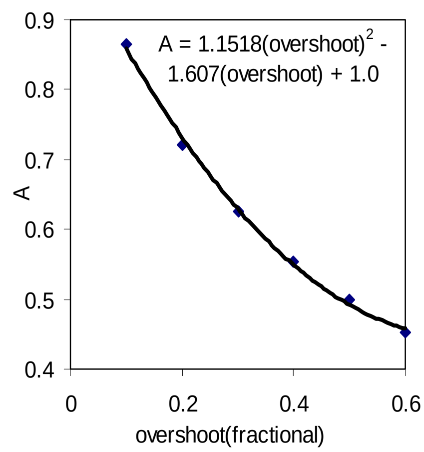


Figure 3. kk_c vs. kk_{c0} for different overshoot

Figure 4. A vs. overshoot

We first seek a relationship for the controller gain k_c. Interestingly, for a fixed value of the overshoot, the ratio k_c/k_{c0} is approximately constant,

$$\frac{k_c}{k_{c0}} = A \tag{9}$$

Note that A is almost independent of the value of τ/θ. This is illustrated in Figure 3 where we plot kk_c (SIMC) as a function of kk_{c0} for the 90 setpoint responses. A is the slope of the line for each overshoot, and is plotted in Figure 4 as a function of the overshoot. The following equation (solid line in Figure 4) fits the data very well,

$$A = \left[1.152(\text{overshoot})^2 - 1.607(\text{overshoot}) + 1.0\right] \tag{10}$$

where the correlation is based on data with fractional overshoot between 0.1 and 0.6. Note that a good fit of k_c is not so important for delay-dominant processes ($\tau/\theta<1$), in the lower left corner in Figure 3, where the integral contribution is the most important.

Next, we want to find a correlation for the integral time. Since the SIMC tuning formula in Eq. (4) uses the minimum of two values, it seems reasonable to look for a similar relationship, that is, to find one that matches processes with a relatively large delay ($\tau_I = \tau$) and one that works well for integrating process ($\tau_I =8\theta$), and then take the minimum.

First, consider processes with relatively large delay ($\tau/\theta<8$ or $\theta>0.125\tau$), where the SIMC-rule is to use $\tau_I = \tau$. From Figure 1, it is clear that for a delay-dominant process ($\theta>\tau$) the integral term (K_I) is most important. This means that it is particularly important to obtain a good value of $K_I = k_c/\tau_I$ in this region. In other words, it is not so important that k_c and τ_I are correct individually, but rather that their ratio K_I is close to the SIMC-value. Inserting $\tau = \tau_I$ in the SIMC rule for k_c in Eq. (6) and solving for τ_I gives

$$\tau_I = 2kk_c\theta \tag{11}$$

To get K_I correct, we here must use the actual value for the controller gain k_c. From (9) we have obtained the correlation $k_c/k_{c0}=A$, where A is given as a function of the overshoot in Eq. (10). However, we also need the value of the process gain k, and to this effect, write

$$kk_c = kk_{c0} \cdot k_c/k_{c0} \tag{12}$$

Here from Eq. (8), $kk_{c0} = b/(1-b)$ where b is obtained from the steady-state value of the setpoint response. In summary, we have following equation for τ_I for a delay dominant process

$$\tau_I = 2A\frac{b}{(1-b)}\theta \tag{13a}$$

where θ is the effective time delay. Similarly, for a lag-dominant (integrating) process ($\tau>8\theta$) the SIMC rule gives

$$\tau_I =8\theta \tag{13b}$$

Equations (13a) and (13b) for the integral time have all known parameters except the effective time delay θ. One could obtain the effective time delay directly from the closed-loop setpoint response, but this may be difficult. Fortunately, as shown in Table 1, there is a good correlation between θ and the peak time t_p which is easier to observe.
Case-a: For processes with a relatively large time delay ($\theta>\tau/8$), the ratio θ/t_p varies between 0.27 and 0.5 (depending on the overshoot and value of τ/θ). We select to use

the value θ=0.43t_p, (note that a large value is more conservative as it increases the integral time). This gives

Process with relatively large time delay: $\tau_I = 0.86\, A \frac{b}{(1-b)} t_p$ (14a)

Case-b: For a lag-dominant process (τ>8θ) we find that θ/t_p varies between 0.25 and 0.36 (depending on the overshoot and value of τ/θ). We select to use the average value θ= 0.305t_p and get

Integrating process: $\tau_I = 2.44 t_p$ (14b)

In conclusion, the integral time τ_I is obtained from the minimum of the above two values and becomes

$$\tau_I = \min\left(0.86A\frac{b}{(1-b)}t_p, 2.44t_p\right) \quad (15)$$

5. Analysis and simulation

Simulations have been conducted for different types of process and the proposed tuning procedure provides reasonable controller settings with respect to both performance and robustness. This section presents only three typical cases to show the effectiveness of the proposed tuning rule. The results of the step test for the controller tuning and corresponding PI setting with M_s value are listed in Table 2. The peak of maximum sensitivity (M_s) is a measure of robustness and is defined as $M_s = \max\left|1/[1+g_p g_c(i\omega)]\right|$; a small M_s value indicates that the stability margin of the control system is large.

The resulting closed-loop PI-response for case E2 is shown in Figure 5. A unit step setpoint change is made at t=0 and a unit step change for a load disturbance at the process input is made at t=100. The recommended PI settings vary somewhat with the overshoot as seen in Table 2. From Figure 5, it is clear that the responses are close to those with the SIMC settings. The resulting PI tunings depend on the overshoot used in the experiment and based on the fitting and the results in example processes (Table 2) we recommend that an overshoot around 0.3 is used in practise.

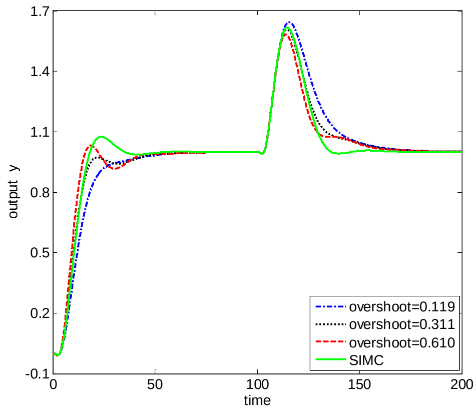


Figure. 5 Response for case E2 process

Table: 1 variation of θ/t_p with τ/θ and overshoot.

	θ/t_p	θ/t_p	θ/t_p
τ/θ	Overshoot =0.1	Overshoot =0.3	Overshoot =0.6
0.1	0.50	0.50	0.50
1.0	0.36	0.41	0.44
8.0	0.27	0.32	0.36
100	0.25	0.30	0.34

6. Conclusion

A simple and new approach for PI controller tuning has been developed. It is based on a single closed-loop setpoint step test using a P-controller. The PI-controller settings are then obtained directly from three characteristic numbers from the setpoint step test: The overshoot, the time to the first peak t_p and the relative steady state change b. The tuning formulas for the proposed **"Shams's setpoint method"** method are:

$$k_c = k_{c0}\left[1.152(\text{overshoot})^2 - 1.607(\text{overshoot}) + 1.0\right]$$

$$\tau_I = \min\left(0.86A\frac{b}{(1-b)}t_p, 2.44t_p\right)$$

The new method works for a wide variety of the processes, except unstable and highly oscillating system. The novelty of the proposed method is that only one experiment in closed-loop is sufficient for getting significant information for controller tuning.
We believe that it could be the simplest and easiest approach for PI controller tuning to use in process industries.

Table 2: PI controller setting for proposed and SIMC method

Case	Process model	k_{c0}	Over-shoot	t_p	b	k_c	τ_I Eq.(14)	$K_I = k_c/\tau_I$	M_s
E1	$\frac{0.2e^{-7.4s}}{s}$	0.40	0.110	29.33	1.0	0.338	71.58(b)	-	1.68
		0.55	0.315	24.09	1.0	0.338	58.77(b)	-	1.70
		0.75	0.610	21.47	1.0	0.342	52.38(b)	-	1.74
		SIMC				0.338	59.2	-	1.70
E2	$\frac{(-s+1)e^{-s}}{(6s+1)(2s+1)(2s+1)}$	0.70	0.119	16.63	0.412	0.583	8.33(a)	-	1.42
		1.30	0.311	13.93	0.565	0.805	9.65(a)	-	1.57
		2.2	0.610	12.27	0.687	1.00	10.60(a)	-	1.74
		SIMC				0.70	7.0	-	1.63
E3	$\frac{e^{-s}}{(0.05s+1)^2}$	0.10	0.10	1.99	0.091	0.086	0.147(a)	0.59	1.70
		0.30	0.30	1.99	0.231	0.189	0.321(a)	0.59	1.62
		0.60	0.60	2.0	0.375	0.275	0.473(a)	0.58	1.65
		SIMC				0.037	0.075(a)	0.49	1.60

7. References

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