CHEMICAL ENGINEERING TRANSACTIONS Volume 24, 2011
Editor Sauro Pierucci
 ISBN 978-88-95608-15-0 ISSN 1974-9791
DOI: 10.3303/CET1124075

A New Approach for PID Controller Tuning from Closed-Loop Setpoint Experiment

Mohammad Shamsuzzoha*, Eid Al-Mutairi

Department of Chemical Engineering, King Fahd University of Petroleum and Minerals, Daharan, 31261 Kingdom of Saudi Arabia, mshams@kfupm.edu.sa

The proposed PID tuning method has similar approach to the recently published paper of Shamsuzzoha and Skogestad (2010). It is one step procedure to obtain the PID setting which gives the better performance and robustness. The method requires one closed-loop step setpoint response experiment using a proportional only controller with gain K_{c0}. Based on simulations for a range of first-order with delay processes, simple correlations have been derived to give PID controller settings. The controller gain (K_c/K_{c0}) is only a function of the overshoot observed in the setpoint experiment. The controller integral and derivative time (τ_I and τ_D) is mainly a function of the time to reach the first peak (t_p). The proposed tuning method shows better performance than Shamsuzzoha and Skogestad (2010) for broad range of processes.

1. Introduction

The proportional, integral, and derivative (PID) controller is widely used in the process industries due to its simplicity, robustness and wide ranges of applicability in the regulatory control layer. One survey of Desborough and Miller (2002) indicates that more than 97% of regulatory controllers utilise the PID algorithm.

There are two approaches for the controller tuning and one may use open-loop or closed-loop plant tests. Most tuning approaches are based on open-loop plant information; typically the plant's gain (k), time constant (τ) and time delay (θ). One popular approach is direct synthesis (Seborg et al., 2004) and other is the IMC-PID tuning method of Rivera et al. (1986). Both the methods give very good performance for setpoint changes but sluggish responses to input (load) disturbances for lag-dominant (including integrating) processes with τ/θ larger than about 10. To improve load disturbance rejection, Skogestad (2003) proposed the modified SIMC method where the integral time is reduced for processes with a large value of the time constant τ.
The other alternative is to use closed-loop experiments. One approach is the classical method of Ziegler-Nichols (1942) which requires very little information about the process. However, there are several disadvantages. First, the system needs to be brought its limit of instability and a number of trials may be needed to bring the system to this point. Another disadvantage is that the Ziegler-Nichols (1942) tunings do not work well on all processes. It is well known that the recommended settings are quite aggressive for lag-dominant (integrating) processes and quite slow for delay-dominant process (Skogestad, 2003). A third disadvantage of the Ziegler-Nichols (1942) method is that it can only be used on processes for which the phase lag exceeds -180 degrees at high frequencies. For example, it does not work on a simple second-order process. Recently, Shamsuzzoha and Skogestad (2010) have developed new procedure for PI/PID tuning method in closed-loop mode which satisfy both the performance and robustness criteria.

Please cite this article as: Shamsuzzoha M. and Al-Mutairi E., 2011, A new approach for pid controller tuning from closed-loop setpoint experiment, Chemical Engineering Transactions, 24, 445-450
DOI: 10.3303/CET1124075

They require only one closed-loop step test to obtain PI controller setting. For the PID tuning setting they need to repeat the experiment with PD controller on the basis of the prior information obtain from P controller test. They recommended adding the derivative action for dominant second-order process only.

Therefore, it is important to have alternative tuning method based on the closed-loop experiment which gives better performance and robustness. In this method it is simple to obtain the PID tuning parameters in one step for improved performance while satisfying the other criteria during the closed-loop experiment like reduces the number of trails, and works for a wide range of processes.

2. IMC-PID Controller Tuning Rule

In process control, a first-order process with time delay is a common representation of the process dynamics:

$$g(s) = \frac{ke^{-\theta s}}{\tau s + 1} \tag{1}$$

Here k is the process gain, τ lag time constant and θ the time delay. Most processes in the chemical industries can be satisfactorily controlled using a PID controller:

$$c(s) = K_c\left(1 + \frac{1}{\tau_I s} + \tau_D s\right) \tag{2}$$

The IMC-PID tuning rule for the first order process with time delay is given as (Seborg et al. 2004).

$$K_c = \frac{2\tau + \theta}{k(2\tau_c + \theta)} \quad \text{(3a)} \qquad \tau_I = \tau_c + \frac{\theta}{2} \quad \text{(3b)} \qquad \tau_D = \frac{\tau\theta}{2\tau + \theta} \quad \text{(3c)}$$

To improve the load disturbance response we recommended to reduce the integral time, for this Skogestad (2003) suggested to modifying the integral time $\tau_I = 4(\tau_c + \theta)$. The recommended value of $\tau_c = \theta$ which gives Ms=1.7 and after simplification tuning rule is

$$K_c = \frac{2\tau + \theta}{3k\theta} \quad \text{(4a)} \qquad \tau_I = \min\left\{\left(\tau + \frac{\theta}{2}\right),\ 8\theta\right\} \quad \text{(4b)} \qquad \tau_D = \frac{\tau\theta}{2\tau + \theta} \quad \text{(4c)}$$

3. Closed-Loop Experiment

This section is devoted for the development of the PID controller based on the closed-loop data which resembles Eq.(4). The proposed procedure is as follows (Shamsuzzoha and Skogestad, 2010):

1. Switch the controller to P-only mode (for example, increase the integral time τ_I to its maximum value or set the integral gain K_I to zero).
2. Make a setpoint change that gives an overshoot between 0.10 (10%) and 0.60 (60%); about 0.30 (30%) is a good value. Record the controller gain K_{c0} used in the experiment.
3. From the closed-loop setpoint response experiment, obtain the following values (see Fig. 1):
   - Fractional overshoot, $(\Delta y_p - \Delta y_\infty)/\Delta y_\infty$
   - Time from setpoint change to reach first peak output (overshoot), t_p
   - Relative steady state output change, $b = \Delta y_\infty/\Delta y_s$.

Here the output variable changes are Δy_s: Setpoint change, Δy_p: Peak output change (at time t_p), Δy_∞: Steady-state output change after setpoint step test.

To find Δy_∞ one needs to wait for the response to settle, which may take some time if the overshoot is relatively large (typically, 0.3 or larger). In such cases, one may stop the experiment when the setpoint response reaches its first minimum (Δy_u) and record the corresponding output,

$\Delta y_\infty = 0.45(\Delta y_p + \Delta y_u)$. (5)

The detail for obtaining Δy_∞ is given in Shamsuzzoha and Skogestad (2010).

4. Correlation between Setpoint Response and the PID-Settings

The objective of this paper is to provide a one step procedure in closed-loop for controller tuning similar to the Shamsuzzoha and Skogestad (2010) and Ziegler-Nichols (1942) method. Thus, the goal is to derive a correlation between the setpoint response data (Fig. 1) and the proposed PID settings in Eq. (4). For this purpose, we considered 15 first-order with delay models $g(s)=ke^{-\theta s}/(\tau s+1)$ that cover a wide range of processes; from delay-dominant to lag-dominant (integrating):

τ/θ=0.1,0.2,0.4,0.8,1.0,1.5,2.0,2.5,3.0,7.5,10.0,20.0,50.0,100

Since we can always scale time with respect to the time delay (θ) and the closed-loop response depends on the product of the process and controller gains (kK_c) we have without loss of generality used in all simulations k=1 and θ=1.

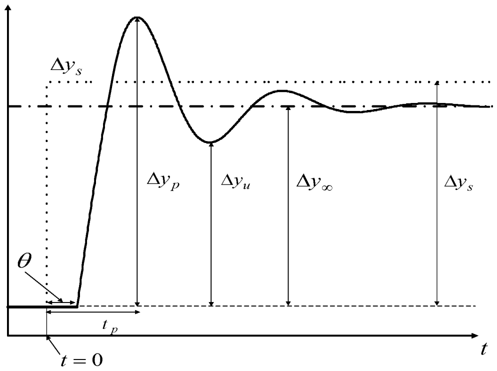

Fig. 1. Closed-loop step setpoint response with P-only control.

For each of the 15 process models (values of τ/θ), we obtained the PID-settings using Eq. (4) with the choice $\tau_c=\theta$. Furthermore, for each of the 15 processes we generated 6 closed-loop step setpoint responses 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, and for each of these we record four data: the P-controller gain K_{c0} used in the experiment, the fractional overshoot, the time to reach the overshoot (t_p), and the relative steady-state change, $b = \Delta y_\infty/\Delta y_s$.

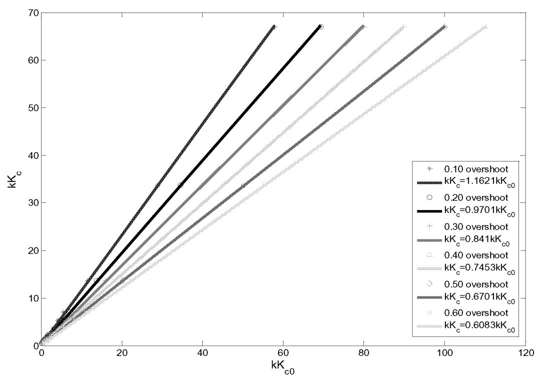

Fig. 2. Relationship between P-controller gain kK_{c0} used in setpoint experiment and corresponding proposed controller gain (Eq. 4a) kK_c.

Controller gain (K_c). We first seek a relationship between the above four data and the corresponding proposed controller gain K_c. Indeed, as illustrated in Fig. 2, where we plot kK_c as a function of kK_{c0} for the 90 setpoint experiments, the ratio K_c/K_{c0} is approximately constant for a fixed value of the overshoot, independent of the value of τ/θ. Thus, we can write

$$\frac{K_c}{K_{c0}}=A \qquad (6)$$

where the ratio A is a function of the overshoot only. In Fig. 3 we plot the value of A, which is obtained as the best fit of the slopes of the lines in Fig. 2, as a function of the overshoot. The following equation (solid line in Fig. 3) fits the data in Fig. 2 well and given as:

$$A=[1.55(\text{overshoot})^2 -2.159\ (\text{overshoot})+1.35] \qquad (7)$$

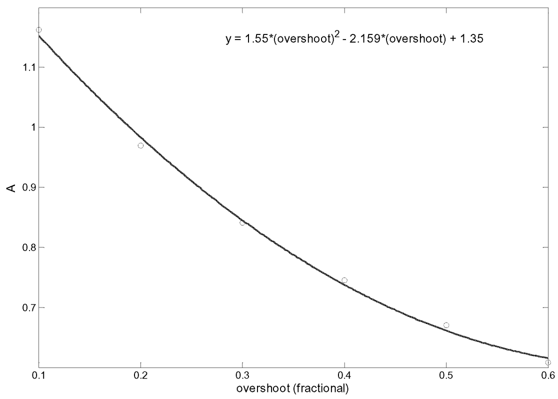

Fig. 3. Variation of A with overshoot using data (slopes) from Fig. 2.

Integral time (τ_I). The proposed method in Eq. (4b) uses the minimum of two values, it seems reasonable to look for a similar relationship, that is, to find one value ($\tau_{I1} = \tau$) for processes with a relatively large delay, and another value ($\tau_{I2} = 8\theta$) for processes with a relatively small delay including integrating processes.

(1) Process with relatively large delay: This case arise when processes have a relatively large delay i.e., $\tau/\theta<8$. From the rearrangement of Eq.(4a) is obtained $\tau = (3kK_c\theta - \theta)/2$. Adding both the side $\theta/2$ and substitute $(\tau+ \theta/2)=\tau_I$, we get

$$\tau_I = 1.5kK_c\theta \qquad (8)$$

In Eq. (8), we also need the value of the process gain k, and to this effect write

$$kK_c= kK_{c0}.K_c/ K_{c0} \qquad (9)$$

Here, the value of the loop gain kK_{c0} for the P-control setpoint experiment is given from the value of b:

$$kK_{c0}=\left|\frac{b}{(1\text{-}b)}\right| \qquad (10)$$

Substituting kK_c from Eq. (10) and K_c/ K_{c0}=A into Eq. (9) and given as

$$\tau_I = 1.5\left|\frac{b}{(1\text{-}b)}\right|\theta \qquad (11)$$

To prove this, the closed-loop setpoint response is $\Delta y/\Delta y_s = gc/(1+gc)$ and with a P-controller with gain K_{c0}, the steady-state value is $\Delta y_\infty/\Delta y_s = kK_{c0}/(1+kK_{c0})=b$ and we derive Eq.(11). The absolute value is included to avoid problems if b>1, as may occur for an unstable process or because of inaccurate data.

For processes with a relatively large time delay ($\tau/\theta<8$), the ratio θ/t_p varies between 0.27, (for τ/θ= 8 with overshoot=0.1) and 0.5 (for τ/θ=0.1 with all overshoots). For the intermediate overshoot of 0.3, the ratio θ/t_p varies between 0.32 and 0.50. A conservative choice would be to use $\theta=0.5t_p$ because a large value increases the integral time. However, to improve performance for processes with smaller time delays, we propose to use $\theta=0.43t_p$ which is only 14% lower than 0.50 (the worst case).
In summary, we have for process with a relatively large time delay:

$$\tau_I = 0.645A\left|\frac{b}{(1-b)}\right|t_p \tag{12}$$

(2) Process with relatively small delay. Both the proposed and Shamsuzzoha and Skogestad (2010) method have same integral action for the lag-dominant process($\tau/\theta>8$) and given as:

$$\tau_{I2}=2.44t_p \tag{13}$$

Conclusion. Therefore, the integral time τ_I is the minimum of the above two values:

$$\tau_I=\min\left(0.645A\left|\frac{b}{(1-b)}\right|t_p,\ 2.44t_p\right) \tag{14}$$

Derivative action (τ_D). The derivative action is recommended in the proposed study for the process having $\tau/\theta\geq1$ to obtain the closed-loop performance improvement. Substitute the value of $\tau=(\tau_I-0.5\theta)$ into $\tau/\theta\geq1$ and after rearrangement $(\tau_I-0.5\theta)/\theta\geq1$. After simplification it is $\tau_I/\theta\geq1.5$, and resulting criteria is $kK_c\geq1.0$. The corresponding closed-loop requisite for the derivative action is given as:

$$A\left|\frac{b}{(1-b)}\right|\geq 1 \tag{15}$$

Case I: For approximately integrating process ($\tau>>\theta$), where the closed-loop time delay θ= 0.305t_p. The derivative time τ_{D1} in Eq. (4c) can be approximated as

$$\tau_{D1}\approx\frac{\tau\theta}{2\tau}=\frac{\theta}{2}=\frac{0.305t_p}{2}=0.15t_p \tag{16}$$

Case II: The processes with a relatively large delay the derivative action is recommended only if $\tau/\theta\geq\theta$. Assuming when $\tau=\theta$, τ_{D2} is given from Eq. (4c) as

$$\tau_{D2}\approx\frac{\theta^2}{2\theta+\theta}=\frac{\theta^2}{3\theta}=\frac{\theta}{3}=\frac{0.43t_p}{3}=0.1433t_p \tag{17}$$

Summary: Since τ_{D1} and τ_{D2} are approximately same and the conservative choice for the selection of τ_D is

$$\tau_D = 0.14t_p \quad if \quad A\left|\frac{b}{(1-b)}\right|\geq 1$$

5. Simulation

The proposed closed-loop tuning method has been tested on broad class of the processes. It provides the acceptable controller setting for all cases with respect to both the performance and robustness. To show the effectiveness of the proposed method one typical case has been discussed as a representative example i.e., high order process with time delay. The simulation has been conducted for three different overshoot (around 0.1, 0.3 and 0.6) and are compared with the recently reported method of Shamsuzzoha and Skogestad (2010).

Example 1: $\dfrac{(-s+1)e^{-s}}{(6s+1)(2s+1)^2}$

Figure 4 has obtained by introducing a unit step change in the set-point at $t = 0$ and an unit step change of load disturbance at $t = 100$ at plant input. It is clear from the figure that the proposed method gives better closed-loop response. There are significant performance improvements in both the case for the disturbance rejection while maintaining setpoint performance. The overshoot around 0.1 typically gives slower and more robust PID-settings, whereas a large overshoot around 0.6 gives fast PID-settings with less robustness. It is good because a more careful step response results in more careful tunings settings.

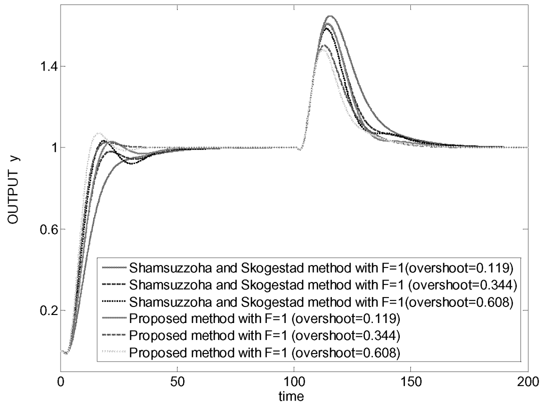

Fig. *4. Responses for Example 1.*

6. Conclusion

A simple approach has been developed for PID controller tuning from the closed-loop setpoint step test using a P-controller with gain K_{c0}. The tuning method is given as: Overshoot= $(\Delta y_p - \Delta y_\infty)/\Delta y_\infty$, Time to reach overshoot (first peak)= t_p, Relative steady state output change, $b = \Delta y_\infty/\Delta y_s$. If one does not want to wait for the system to reach steady state, use the estimate $\Delta y_\infty = 0.45(\Delta y_p + \Delta y_u)$.

$K_c = K_{c0}A$, where $A = [1.55(\text{overshoot})^2 - 2.159\,(\text{overshoot}) + 1.35]$

$$\tau_I = \min\left(0.645A\left|\frac{b}{(1-b)}\right|t_p,\ 2.44t_p\right), \quad \tau_D = 0.14t_p \quad if \quad A\left|\frac{b}{(1-b)}\right| \geq 1$$

The proposed method works well for a wide variety of the processes including the integrating, high-order, inverse response, unstable and oscillating process.

Acknowledgement: The author would like to acknowledge the support (**Project Number: SB101016**) provided by the Deanship of Scientific Research at KFUPM.

References

Desborough, L. D., Miller, R. M., 2002, Increasing customer value of industrial control performance monitoring—Honeywell's experience. Chemical Process Control–VI (Tuscon, Arizona, Jan. 2001), Vol. 98, AIChE Symposium Series No. 326, USA.

Rivera, D. E., Morari, M., Skogestad, S., 1986, Internal model control. 4. PID controller design, Ind. Eng. Chem. Res., 25 (1), 252–265.

Seborg, D. E., Edgar, T. F., Mellichamp, D. A., 2004, Process Dynamics and Control, 2nd ed., John Wiley & Sons, New York, U.S.A.

Shamsuzzoha, M., Skogestad S., 2010, The setpoint overshoot method: A simple and fast closed-loop approach for PID tuning, Journal of Process Control, 20, 1220–1234.

Skogestad, S., 2003, Simple analytic rules for model reduction and PID controller tuning, Journal of Process Control, 13, 291–309.

Ziegler, J. G., Nichols, N. B., 1942, Optimum settings for automatic controllers. Trans. ASME, 64, 759-768.