Practical Strategies for Using Signal Filters with Available Industrial Controllers

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ABSTRACT

Signal filters improve controller performance by reducing the impact of noise or random error in the measured process variable. These filters may be placed upon either the measured process variable or the controller output. Directly or indirectly, signal filters limit the large controller output moves caused by derivative action upon noisy measurements. Even if the noise appears not to cause performance problems, the filter reduces fluctuations in the controller output that wear the final control element. This paper uses mathematical analysis of closed-loop transfer functions combined with simulation studies of non-self regulating processes to demonstrate practical strategies for using available industrial controllers with controller output signal filters either internal or external to the controller.

Many industrial controllers include a signal filter as the fourth mode of a proportional-integral-derivative (PID) with Filter controller. These exist in a variety of forms depending upon the placement of the derivative and signal filter terms. In the Ideal and Interacting forms, the controller consists of a single ordinary differential equation (ODE) including all four terms. In the Parallel form, the controller consists of a system of two ODEs with the proportional and integral terms comprising one ODE and the derivative and signal filter terms comprising a second ODE. The output of the Parallel controller form equals the sum of the outputs of the two ODEs. The Parallel form filters controller output changes resulting only from derivative action while the Ideal and Interacting forms filter changes resulting from proportional, integral, and derivative action combined.

Novel contributions of this work are derived Internal Model Control (IMC) tuning correlations for the Parallel form of the PID with Filter controller for non self-regulating systems. These derived correlations are necessary to accurately and dependably tune commonly-used Parallel form industrial controllers manufactured by ABB, Bailey, Emerson, and Honeywell, among others, for use in non-self regulating processes. These new correlations allow Parallel form controller users to employ IMC tuning methods similar to those already available for the Ideal and Interacting forms.

This paper demonstrates the use of signal filters both internal and external to the controller through mathematical analysis of closed-loop transfer functions supported by simulation results for non-self regulating processes. If a four mode PID with Filter controller is not available in an industrial process, the paper demonstrates how a three mode PID controller combines with a signal filter external to the controller to essentially create a four mode PID with Filter controller.

The tuning and performance of each of the PID with Filter controller forms is detailed using simulation studies on non self-regulating processes.

INTRODUCTION

Self-regulating processes seek a natural steady state operating level in the open loop if the manipulated and disturbance variables remain constant for a sufficient period of time. Conversely, non-self regulating (or integrating) processes do not seek such a natural steady state. These processes move in an unbounded manner when perturbed in the open loop by a manipulated or disturbance variable. A pumped tank is a well-known example of such a non-self regulating process.

For non-self regulating processes, Rice and Cooper [1] introduced IMC tuning correlations for the Ideal and Interacting forms of the PID with Filter controller shown in Eq. 1 and 2, respectively. This paper extends the IMC tuning correlations to the Parallel form shown in Eq. 3 for non-self regulating processes. Furthermore, this paper demonstrates how an Ideal PID with Filter controller may be formed using an Ideal PID controller (without filter) combined with an external filter.

Generalized PID with Filter Controller Forms

The proportional-integral-derivative (PID) controller continues to be widely-used in industry because it effectively controls a wide variety of processes while remaining easy to understand and tune. Often, industrial PID controllers include a signal filter as a fourth mode, as indicated by the derivative filter parameter, α, in Eq. 1-3. Differences in the placement of the derivative and filter terms lead to these three PID with Filter controller forms [1-6], shown in both the Laplace and time domains:

Ideal

$$U(s) = K_C\left[1+\frac{1}{\tau_I s}+\tau_D s\right]\left(\frac{1}{\alpha\tau_D s+1}\right)E(s) \qquad \text{(1a)}$$

$$u(t) = bias + K_C e(t) + \frac{K_C}{\tau_I}\int e(t)dt + K_C\tau_D\frac{de(t)}{dt} - \alpha\tau_D\frac{du(t)}{dt} \qquad \text{(1b)}$$

Interacting

$$U(s) = K_C\left[1+\frac{1}{\tau_I s}\right]\left(\frac{\tau_D s+1}{\alpha\tau_D s+1}\right)E(s) \qquad \text{(2a)}$$

$$u(t) = bias + K_C\left(1+\frac{\tau_D}{\tau_I}\right)e + \frac{K_C}{\tau_I}\int e(t)dt + K_C\tau_D\frac{de(t)}{dt} - \alpha\tau_D\frac{du(t)}{dt} \qquad \text{(2b)}$$

$$U(s)=K_C\left[1+\frac{1}{\tau_I s}+\frac{\tau_D s}{\alpha\tau_D s+1}\right]E(s) \qquad (3a)$$

Parallel

$$\left\{\begin{aligned}&u_{PI}(t) = bias + K_C e(t) + \frac{K_C}{\tau_I}\int e(t)dt\\&u_D(t)=K_C\tau_D\frac{de(t)}{dt}-\alpha\tau_D\frac{du_D(t)}{dt}\\&u(t)=u_{PI}(t)+u_D(t)\end{aligned}\right\} \qquad (3b)$$

Note that the Ideal and Parallel forms shown in Eq. 1 and 3, respectively, are equivalent without the filter term ($\alpha = 0$). Note also that the Ideal form can be converted to the Interacting form shown in Eq. 2. Therefore, the Ideal and Interacting forms are simply different expressions of the same controller equation. In contrast, the Parallel form is a fundamentally different controller equation because of the placement of the filter. Observe this difference in the system of two ordinary differential equations (ODEs) in Eq. 3b versus the single ODE for the Ideal and Parallel forms in Eq. 1b and 2b.

There are many examples [2] of industrial Parallel form PID with Filter controllers including: ABB Masterpiece 200/1; Bailey Function Code 156 Non-Interacting PID; Emerson Delta V Parallel PID; Honeywell Experion PKS Equations A, B, and C; Honeywell TDC 3000 Non-Interactive Equations A, B, and C; and Siemens PCS7 CTRL_PID. Therefore, there is clearly a need for extending IMC tuning to the Parallel form.

IMC TUNING

The Internal Model Control (IMC) method is popular for tuning PID controllers [7-9]. Observe how the IMC block diagram in Fig. 1 may be converted into a conventional feedback control structure when the internal models represented by $G_M(s)$ are removed.

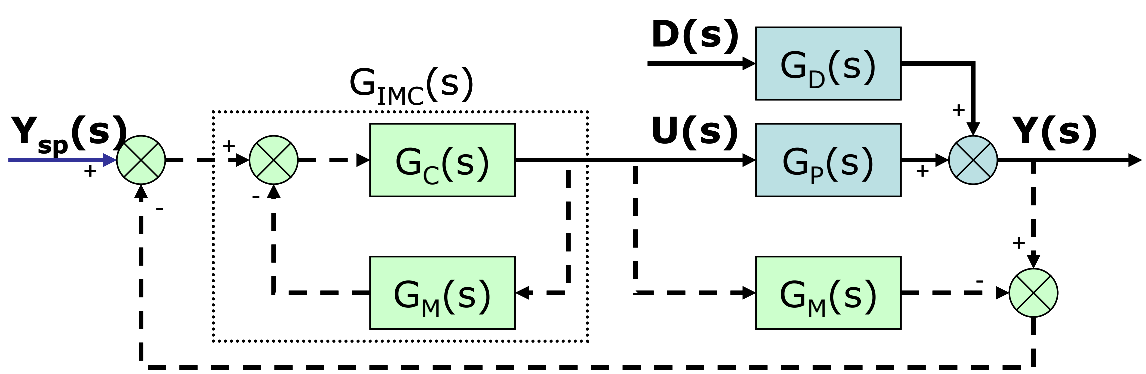

Figure 1. IMC Block Diagram

Using the structure shown in Fig. 1 and the procedure outlined in Chien and Fruehauf [9], the following tuning rules are derived for the three forms of the PID with Filter controller. For non-self regulating processes, these rules use a First Order plus Dead Time (FOPDT) Integrator model for $G_M(s)$, expressed in terms of the integrator gain, K_P^*, and the dead time, θ_P, in Eq. 4.

$$Y(s) = \frac{K_P^* e^{-\theta_P s}}{s} U(s) \tag{4}$$

The following IMC tuning correlations for the Parallel form of the PID with Filter controller for non-self regulating processes are a novel contribution of this work. These tuning correlations are presented alongside those for the Ideal and Interacting forms [1].

IMC Tuning for PID with Filter Controllers for Non-Self Regulating Processes

The first step in tuning a PID with Filter controller for a non-self regulating process is to collect dynamic data from your process as near as practical to the design level of operation. For non-self regulating processes, this data is often collected in closed loop to maintain stability. The second step is to fit a FOPDT Integrator model, as shown in Eq. 4, to the data collected.

Once the FOPDT Integrator model parameters have been determined, the third step is to specify the closed loop time constant, τ_{CL}. Use this parameter to adjust controller performance. Increase τ_{CL} to produce a slower, more conservative response with a longer settling time. Conversely, decrease τ_{CL} to produce a faster and more aggressive response with a shorter settling time. The choice of is dependent upon an understanding of the nature of the process and an evaluation of the objectives and constraints for closed loop performance. τ_{CL} may be computed in terms of θ_P using Eq. 5 [10].

$$\tau_{CL} = \theta_P \sqrt{10} \tag{5}$$

To apply these tuning correlations, it is important to determine the form of your PID with Filter controller. The next step in calculating IMC tuning parameters is the calculation of K_F, the filter gain, based on θ_P and τ_{CL} using Eq. 6. K_F remains equal for all three forms.

Ideal, Interacting and Parallel

$$K_F = \alpha\tau_D = \frac{\theta_P \tau_C^2}{2\tau_C^2 + 4\theta_P\tau_C + \theta_P^2} \tag{6}$$

The reset time, τ_I, has a different tuning equation for each of the three forms. All three equations are expressed in terms of θ_P and τ_{CL}. The Parallel form in Eq. 7c differs from the Ideal form in Eq. 7a only in the subtraction of K_F in the Parallel form.

Ideal

$$\tau_I = 2\tau_C + \frac{3}{2}\theta_P \tag{7a}$$

Interacting

$$\tau_I = 2\tau_C + \theta_P \tag{7b}$$

Parallel

$$\tau_I = 2\tau_C + \frac{3}{2}\theta_P - K_F \tag{7c}$$

Equation 8 expresses the controller gain, K_C, in terms of K_P^*, θ_P, τ_{CL}, and τ_I for all three forms.

Ideal, Interacting and Parallel

$$K_C = \frac{2\tau_I}{K_P^*\left(2\tau_C^2 + 4\theta_P\tau_C + \theta_P^2\right)} \tag{8}$$

The derivative time, τ_D, has two different tuning equations in terms of θ_P, τ_{CL}, and τ_I. The Ideal and Interacting forms use Eq. 9a while the Parallel form uses Eq. 9b. The equations differ only by the subtraction of K_F in the Parallel form.

Ideal and Interacting

$$\tau_D = \theta_P\left(\tau_C + \frac{1}{2}\theta_P\right)\frac{1}{\tau_I} \tag{9a}$$

Parallel

$$\tau_D = \theta_P\left(\tau_C + \frac{1}{2}\theta_P\right)\frac{1}{\tau_I} - K_F \tag{9b}$$

Equation 10 expresses the filter coefficient, α, in terms of K_F and τ_D for all three forms. Because K_F is equal for all three forms, the product of α and τ_D remains equal for all three forms.

Ideal, Interacting and Parallel

$$\alpha = \frac{K_F}{\tau_D} \tag{10}$$

Equations 6 through 10 demonstrate the similarities and differences between the tuning correlations for the Ideal, Interacting, and Parallel forms of the PID with Filter controller algorithm.

While these tunings are derived assuming derivative on error, these tunings are applicable to derivative on measurement forms of the PID with Filter controller. The derivative of the set point signal is the only difference between these two forms. If the set point signal remains steady, the derivative of the set point signal remains zero and there is no difference between the forms. To avoid the derivative kick caused by the derivative when the set point changes, the examples presented in this paper use derivative on measurement.

Differences between Parallel and Ideal Tunings for Non-Self Regulating Processes

It is important to understand the difference between the tuning correlations for the Parallel and Ideal forms of the PID with Filter controller because the two are equivalent when the filter term is removed.

To facilitate this comparison, scale the closed loop time constant, τ_{CL}, by the dead time, θ_P, to produce the dimensionless ratio, k, as shown in Eq. 11. Increase k for a more conservative response and decrease k for a more aggressive response.

$$k = \frac{\tau_{CL}}{\theta_P} \tag{11}$$

The first step in comparing the forms is to convert Eq. 6 to Eq. 12 by expressing the filter gain, K_F, scaled by θ_P as a function of k. Note that f(k) approaches 0 as k approaches 0. Because the numerator and denominator are polynomials of the same order, f(k) approaches 1 as k approaches infinity.

$$f(k) = \frac{K_F}{\theta_P} = \frac{k^2}{2k^2 + 4k + 1} \tag{12}$$

Express the reset times, $\tau_{I,Ideal}$ and $\tau_{I,Parallel}$, as functions of k based upon Eq. 7a and 7c, respectively. Using these functions, compute Eq. 13, the ratio of $\tau_{I,Parallel}$ to $\tau_{I,Ideal}$. As k approaches 0, the ratio approaches 1. As k approaches infinity, the ratio also approaches 1. Based on Eq. 8, the ratio of $K_{C,Parallel}$ to $K_{C,Ideal}$ equals the ratio of $\tau_{I,Parallel}$ to $\tau_{I,Ideal}$.

$$\frac{K_{C,Parallel}}{K_{C,Ideal}} = \frac{\tau_{I,Parallel}}{\tau_{I,Ideal}} = 1 - \frac{f(k)}{2k + \frac{3}{2}} \tag{13}$$

To evaluate the difference between $\tau_{I,Parallel}$ and $\tau_{I,Ideal}$, observe the plot of Eq. 13 versus k shown in Fig. 2. Notice that the ratio of $\tau_{I,Parallel}$ to $\tau_{I,Ideal}$ approaches 1 as k approaches 0. As k increases from 0, the ratio drops sharply to a minimum of about 0.955 at a k value around 1.6. As k increases from 1.6, the ratio grows gradually to approach 1 as k approaches infinity. The ratio never exceeds 1. At the minimum ratio, the difference between $\tau_{I,Parallel}$ and $\tau_{I,Ideal}$ reaches its maximum value but $\tau_{I,Parallel}$ is only 4.5% less than $\tau_{I,Ideal}$.

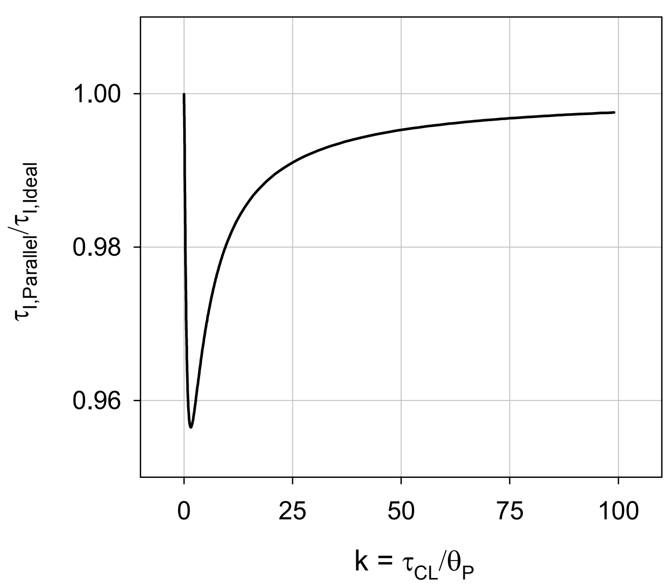

Figure 2. Difference Between $\tau_{I,Parallel}$ and $\tau_{I,Ideal}$

Express the derivative times, $\tau_{D,Ideal}$ and $\tau_{D,Parallel}$, as functions of k based upon Eq. 9a and 9b, respectively. Using these functions, compute Eq. 14, the ratio of $\tau_{D,Parallel}$ to $\tau_{D,Ideal}$. Note that the first of two terms is the reciprocal of the ratio of $\tau_{I,Parallel}$ to $\tau_{I,Ideal}$. From Fig. 2, observe that the ratio remains very close to 1 as does its reciprocal. Therefore, the first term remains approximately equal to 1 for all k. As k approaches 0, the second term approaches 0 and the ratio approaches 1. As k approaches infinity, the second term approaches 1 and the ratio approaches 0. Based on Eq. 10, the ratio of $\alpha_{Parallel}$ to α_{Ideal} equals the reciprocal of the ratio of $\tau_{D,Parallel}$ to $\tau_{D,Ideal}$.

$$\frac{\tau_{D,Parallel}}{\tau_{D,Ideal}} = \frac{1}{\left(\dfrac{\alpha_{Parallel}}{\alpha_{Ideal}}\right)} = \frac{1}{\left(\dfrac{\tau_{I,Parallel}}{\tau_{I,Ideal}}\right)} - \frac{f(k)}{\left(\dfrac{k+\frac{1}{2}}{2k+\frac{3}{2}}\right)} \tag{14}$$

To understand the difference between $\tau_{D,Parallel}$ to $\tau_{D,Ideal}$, observe the plot of Eq. 14 versus k shown in Fig. 3. As k approaches 0, the ratio approaches 1 as expected. As k approaches infinity, the ratio approaches 0 as expected. The closed loop time constant, τ_{CL}, as expressed in Eq. 5, results in k of about 3.16. At this recommended value, $\tau_{D,Parallel}$ equals only 40% of the $\tau_{D,Ideal}$ value.

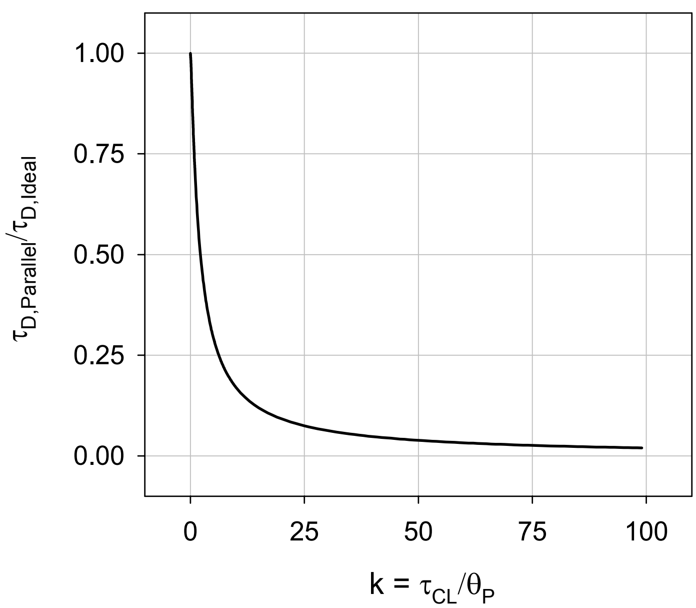

Figure 3. Difference Between $\tau_{D,Parallel}$ and $\tau_{D,Ideal}$

Figures 2 and 3, along with Eq. 12-14 demonstrate the similarities and differences between the Parallel and Ideal forms of the PID with Filter controller. The tuning correlations produce similar values for K_C and τ_I. As the choice for the closed loop time constant, τ_{CL}, increases for a more conservative controller, the difference between the τ_D and α values computed for the Parallel and Ideal forms increases.

USING IMC TUNINGS WITH EXTERNAL FILTERS

In industry, many controllers take the form of one of PID with Filter controller forms shown in Eq. 1-3. However, there are industrial PID controllers that do not include a filter term. With noisy measurements very likely in an industrial environment, this makes derivative action difficult without a filter. Without the filter, the derivative action reacts to the noisy signal and may produce great amounts of controller output movement depending upon the amount of noise present and the controller tuning. A PID controller may be combined with an external filter on either the controller output or the measured process variable to replicate a PID with Filter controller.

Figures 4 and 5 display the Ideal and Parallel PID with Filter controllers from Eq. 1 and 3 in closed loop block diagrams with a process modeled by $G_P(s)$ and a disturbance modeled by $G_D(s)$. In each, the controller is split into three parts: a proportional-integral block, $G_{C,PI}(s)$, a derivative block, $G_{C,D}(s)$, and a filter block, $G_{C,F}(s)$. These blocks are specified for both controllers, according to Eq. 15-17. Notice that the only difference between the two controllers is the placement of $G_{C,F}(s)$.

$$G_{C,PI}(\mathrm{s}) = K_C\left[1+\frac{1}{\tau_I s}\right] \tag{15}$$

$$G_{C,D}(\mathrm{s}) = K_C \tau_D s \tag{16}$$

$$G_{C,F}(\mathrm{s}) = \frac{1}{\alpha \tau_D s + 1} \tag{17}$$

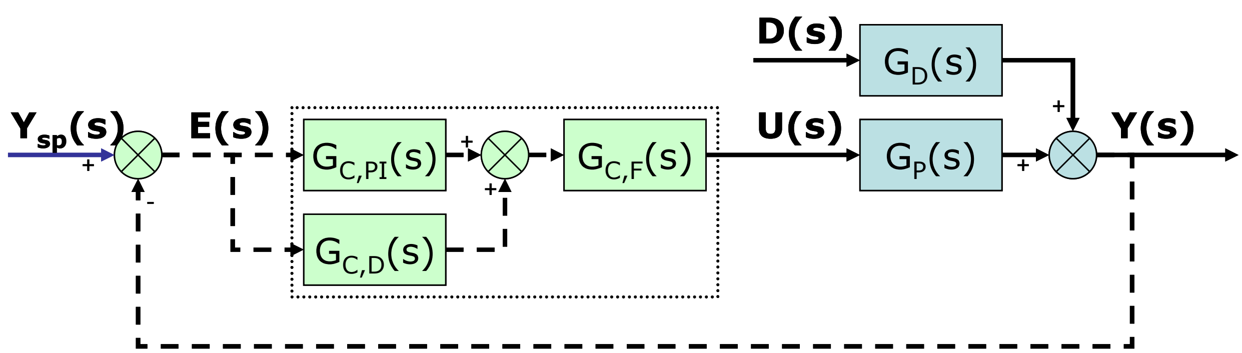

Figure 4. Closed Loop Process with Ideal PID with Filter Controller

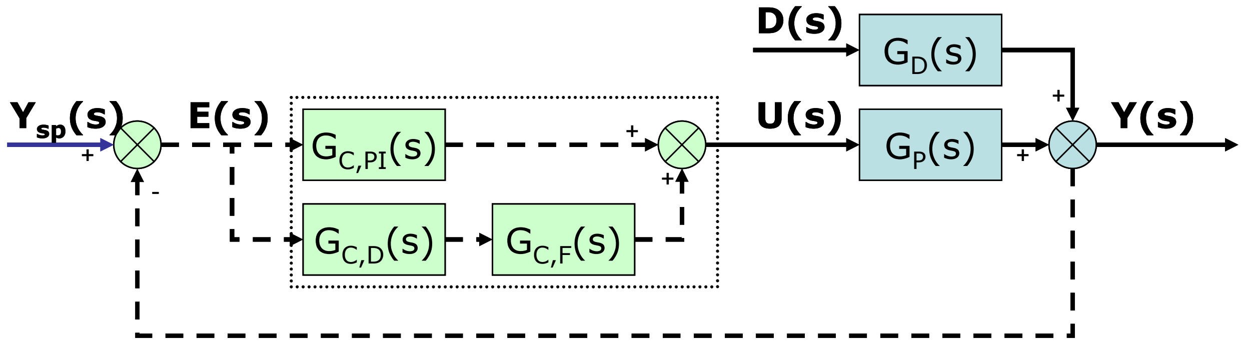

Figure 5. Closed Loop Process with Parallel PID with Filter Controller

The closed loop block diagrams shown for the Ideal and Parallel forms in Fig. 4 and 5 may also be described using the transfer functions in Eq. 15 and 16, respectively.

$$Y(\mathrm{s}) = \frac{G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_{C,F}(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_{C,F}(s)}Y_{SP}(s) + \frac{G_D(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_{C,F}(s)}D(s) \qquad (15)$$

$$Y(\mathrm{s}) = \frac{G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)G_{C,F}(s)\right]}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)G_{C,F}(s)\right]}Y_{SP}(s) + \frac{G_D(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)G_{C,F}(s)\right]}D(s) \qquad (16)$$

The Ideal form of the PID with Filter controller shown in Fig. 4 and Eq. 15 may be replicated by adding an external filter, $G_F(s)$, on either the controller output, U(s), or the measured process variable, Y(s), to the process alongside a PID controller. The addition of a filter on the controller output is straightforward as shown by the block diagram in Fig. 6 and the transfer functions in Eq. 17.

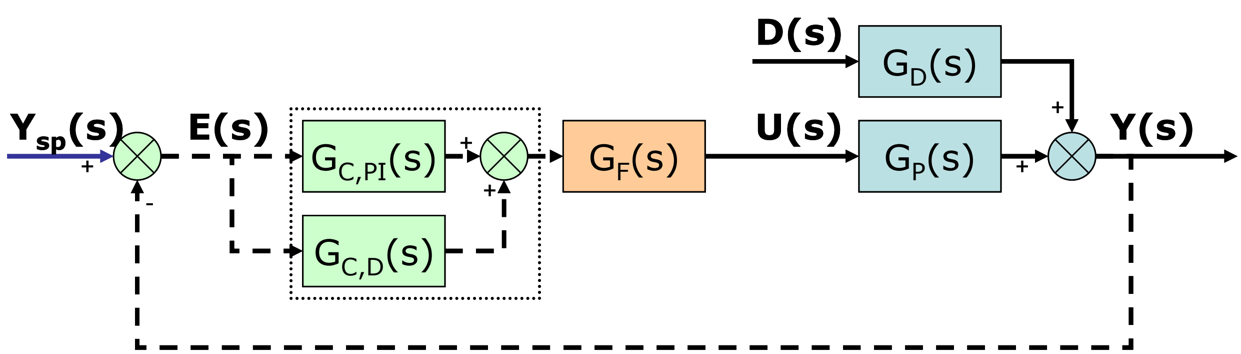

Figure 6. Closed Loop Process with PID Controller and External Filter on U(s)

$$Y(\mathrm{s}) = \frac{G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_F(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_F(s)}Y_{SP}(s) + \frac{G_D(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_F(s)}D(s) \qquad (17)$$

By equating Eq. 15 and 17, it is clear that the filter, $G_F(s)$, may be specified as first order filter matching the $G_{C,F}(s)$ for the Ideal PID with Filter controller as shown in Eq. 18.

$$G_F(s) = G_{C,F}(s) = \frac{1}{\alpha_{Ideal}\tau_{D,Ideal}s + 1} \tag{18}$$

Similarly, an Ideal PID with Filter controller may be replicated using an external filter on the measured process variable, Y(s) as shown by Fig. 7 and Eq. 19.

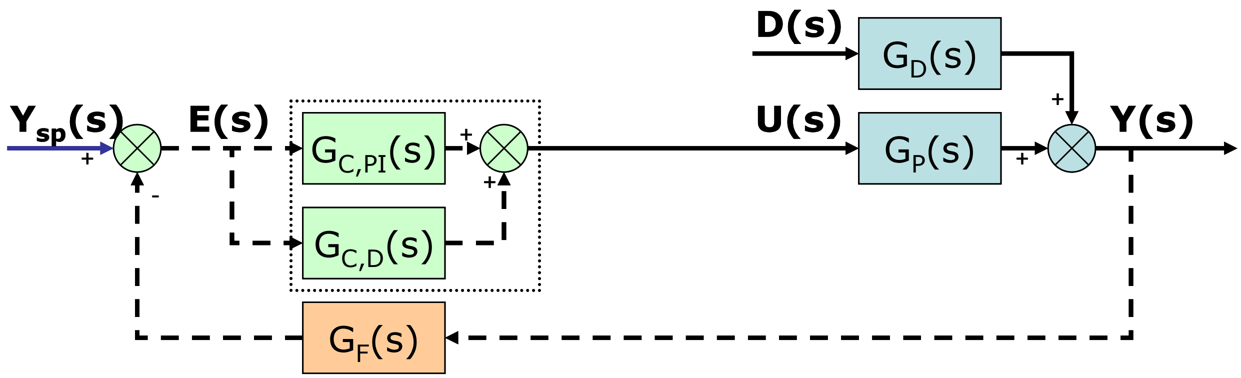

Figure 7. Closed Loop Process with PID Controller and External Filter on Y(s)

$$Y(s) = \frac{G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_F(s)} Y_{SP}(s) + \frac{G_D(s)}{1 + G_P(s)\left[G_{C,PI}(s) + G_{C,D}(s)\right]G_F(s)} D(s) \tag{19}$$

Note that the only difference between placing the external filter on U(s) and Y(s) is the $G_F(s)$ that appears in the numerator of the $Y(s)/Y_{SP}(s)$ transfer function in Eq. 17 but not Eq. 19. This results in filtering of the set point signal in Eq. 17 but not in Eq. 19. Assuming that the set point remains steady, this filtering has little impact upon controller performance. By equating the denominators in Eq. 15 and 19, it is clear that the external filter on Y(s) may also be specified as a first order filter matching the $G_{C,F}(s)$ for the Ideal PID with Filter controller as shown in Eq. 20.

$$G_F(s) = G_{C,F}(s) = \frac{1}{\alpha_{Ideal}\tau_{D,Ideal}s + 1} \tag{20}$$

NON SELF-REGULATING EXAMPLE PROCESS 1 – PUMPED TANK

The first example simulates a 10 m pumped tank using the linear model shown as Eq. 21 with user-specified limits for the measurement and physical process limits.

$$G_{P1}(s) = \frac{\left(-0.022\ \mathrm{m}/\%\mathrm{CO}\right)e^{-(1.1\ \mathrm{min})s}}{s} \tag{21}$$

As depicted in Fig. 8 below, liquid continually feeds into the tank at a constant rate while a pump empties the tank at a variable rate. The level in the tank only remains steady if the discharge flow rate through the pump equals the feed rate. If the discharge flow rate exceeds the feed rate, the imbalance causes the tank to drain until empty. Similarly, the tank fills until overfilled if the feed rate exceeds the discharge flow rate. Therefore, this is an excellent example of a non self-regulating, or integrating, process.

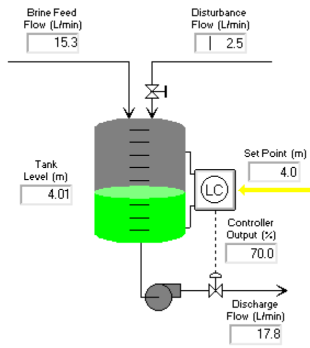

Figure 8. Pumped Tank Example

This example process uses IMC tuning parameters based upon the closed loop time constant, τ_{CL}, calculated using Eq. 5. Table 1 lists the tuning parameters used for the Ideal, Interacting, and Parallel forms of the PID with Filter controller along with the parameters for the Ideal form of the PID controller (without filter).

Table 1. IMC Tunings PID and PID with Filter Controllers on Pumped Tank

	Controller Gain, K_C (%CO/m)	**Reset Time, τ_I** (min)	**Derivative Time, τ_D** (min)	**Filter Coefficient, α**
Ideal PID w/ Filter	-19.3	8.6	0.51	0.64
Interacting PID w/ Filter	-18.1	8.0	0.55	0.59
Parallel PID w/ Filter	-18.5	8.3	0.21	1.57
Ideal PID	-22.6	8.1	0.51	

As discussed previously, the derivative time, τ_D, is significantly smaller for the Parallel form than it is for the Ideal form. Conversely, the filter coefficient, α, is significantly larger for the Parallel form than it is for the Ideal form.

Figure 9 demonstrates the performance using the three PID with Filter controllers and tunings listed in Table 1 in response to a set point step from 4.0 m to 4.5 m. A normally distributed noise of 0.12 m span (6σ) is applied to the level measurement to demonstrate the ability of the PID with Filter controllers to handle noise.

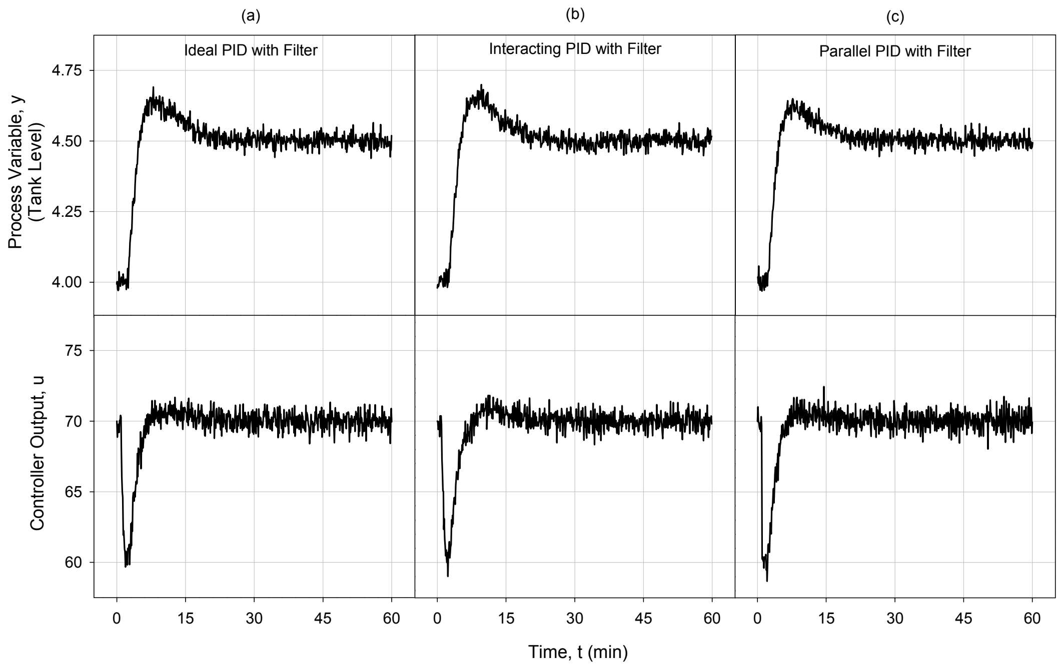

Figure 9. PID with Filter Controllers using Table 1 Tuning Parameters

In Fig. 9, notice that the Ideal (a), Interacting (b), and Parallel (c) forms of the PID with Filter controller perform similarly. The slight differences observed are expected due to the random noise present. This similarity is due to the use of the same closed loop time constant, τ_{CL}, in the IMC tuning correlations for each controller form. The filter does not eliminate the appearance of chatter in the controller output signal due to the noise in the level measurement. However, it clearly reduces the controller output movement as compared to the PID controller (without filter) shown in Figure 10 while achieving a similar response in the level measurement.

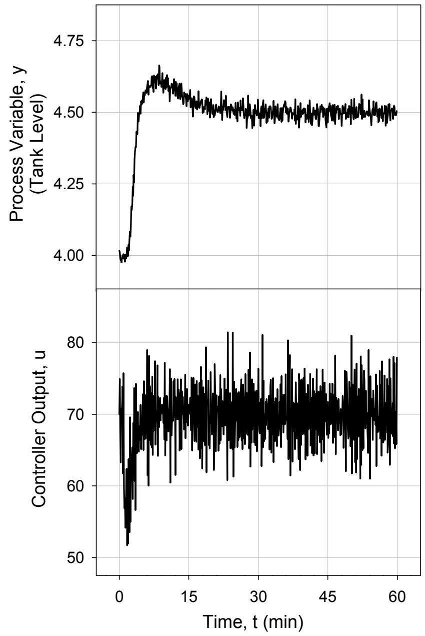

Figure 10. PID (without Filter) Performance with Noise

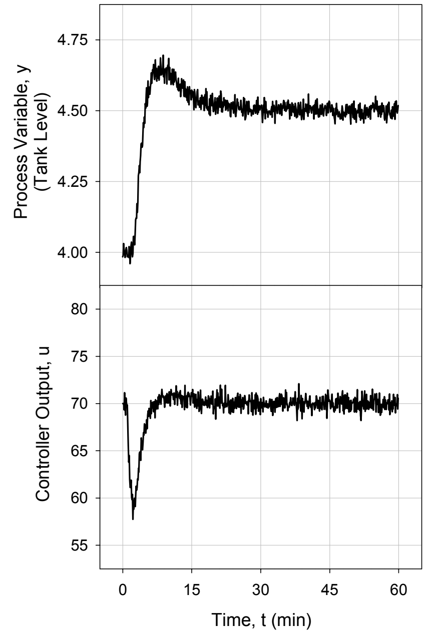

Figure 11. PID Controller with External Filter on Controller Output, u(t), Signal

A comparison of Fig. 9 and 10 clearly demonstrates that a four-mode PID with Filter controller produces considerably less chatter or movement in the controller output variable than a three-mode PID controller without filter. However, some industrial PID controllers, including the Bailey Function Code 19 [2], are three-mode and do not include a filter term.

Figures 11 and 12 demonstrate the transformation of such three-mode PID controllers into effective four-mode PID with Filter controllers with the addition of external filters on the controller output signal and the process variable measure signal, respectively. In both strategies, the Ideal PID controller uses Ideal PID with Filter controller tunings for K_C, τ_I, and τ_D from Table 1. According to Eq. 18 and 20, both strategies also specify the external filter as a first order filter with a filter time constant equal to the product $\alpha\tau_D$ using the Ideal PID with Filter controller tunings in Table 1.

Note how the performance with the external filter on controller output in Fig. 11 matches the performance of the Ideal PID with Filter controller in Fig. 9a as expected.

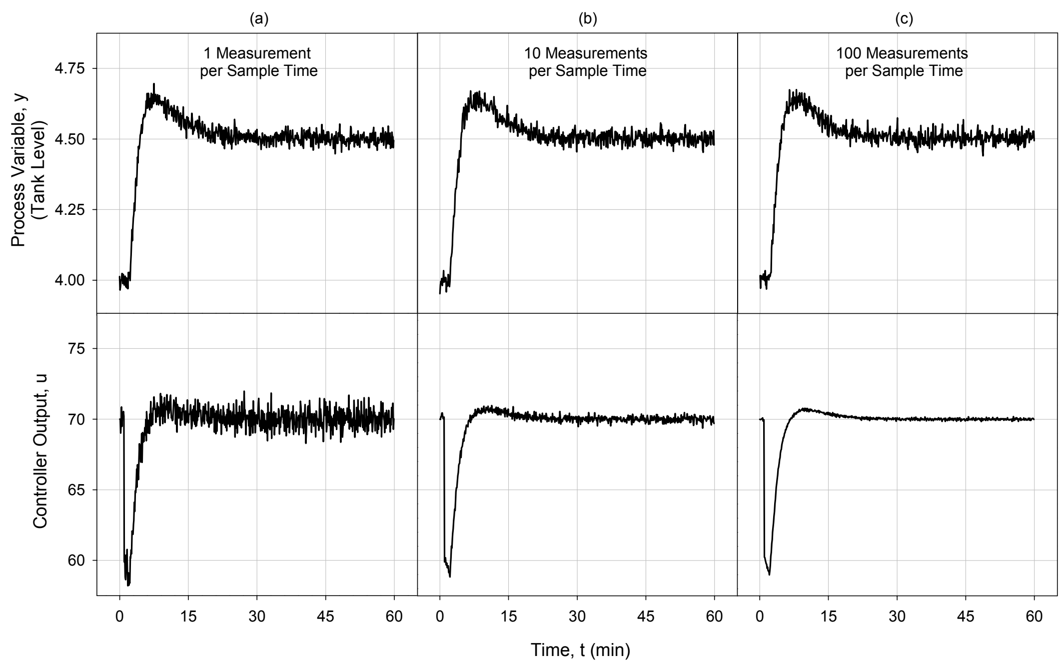

Figure 12. PID Controller with External Filter on Process Variable, y(t), Measurement Signal

In Fig. 12, notice how the performance of the external filter on the process variable measurement signal improves as the number of times the measurement signal is observed and filtered increases per controller sample time. In Fig. 12a, the filter observes changes in the measurement signal only every sample time as the controller does, the performance matches the Ideal PID with Filter performance shown in Fig. 9a. In Fig. 12b, the filter observes 10 changes in the measurement signal for every change the controller observes and the filtering improves with less movement in the controller output signal. In Fig. 12c, the filter observes 100 changes in the measurement signal for every change the controller observes and the filtering further improves with even less movement in the controller output signal.

NON SELF-REGULATING EXAMPLE PROCESS 2

These IMC tuning correlations for PID with Filter controllers are applied to the non-self regulating process listed in Eq. 22. This process is widely published for use in comparing PID controller tunings [1, 11-14]. Rice and Cooper [1] compared the IMC tunings for the Ideal and Interacting forms of the PID with Filter controller with following published tunings for this process: Luyben [13]; Wang and Cluett [15]; and Ziegler-Nichols [13]. This paper builds upon previous work [1] by demonstrating the performance using IMC tunings for the Parallel form of the PID with Filter controller.

$$G_{P2}(s) = \frac{0.0506e^{-6s}}{s} \tag{22}$$

In accordance with the rule shown in Eq. 5, the closed loop time constant, τ_{CL}, is specified to be 19 min. The tuning parameters found in Table 2 are based upon this τ_{CL} value using the IMC tuning correlations for the three PID with Filter forms as detailed in Eq. 6-10.

Table 2. IMC Tunings PID with Filter Controllers in Example 2

	Controller Gain, K_C (%CO/%PV)	**Reset Time, τ_I** (min)	**Derivative Time, τ_D** (min)	**Filter Coefficient, α**
Ideal PID w/ Filter	1.53	47	2.8	0.64
Interacting PID w/ Filter	1.43	44	3.0	0.59
Parallel PID w/ Filter	1.47	45	1.14	1.57

Notice how the controller gains and reset times are relatively similar for the three forms. The derivative time, τ_D, is significantly smaller for the Parallel form while the filter parameter, α, is significantly larger. These observations are consistent with those observed in Example 1 and predicted in Eq. 11-14 and Fig. 2-3. Using the tuning parameters in Table 2, Fig. 13 demonstrates the performance for each of the PID with Filter Controllers in response to set point step from 50 to 51 with a 0.12 span (6σ) normally distributed measurement noise.

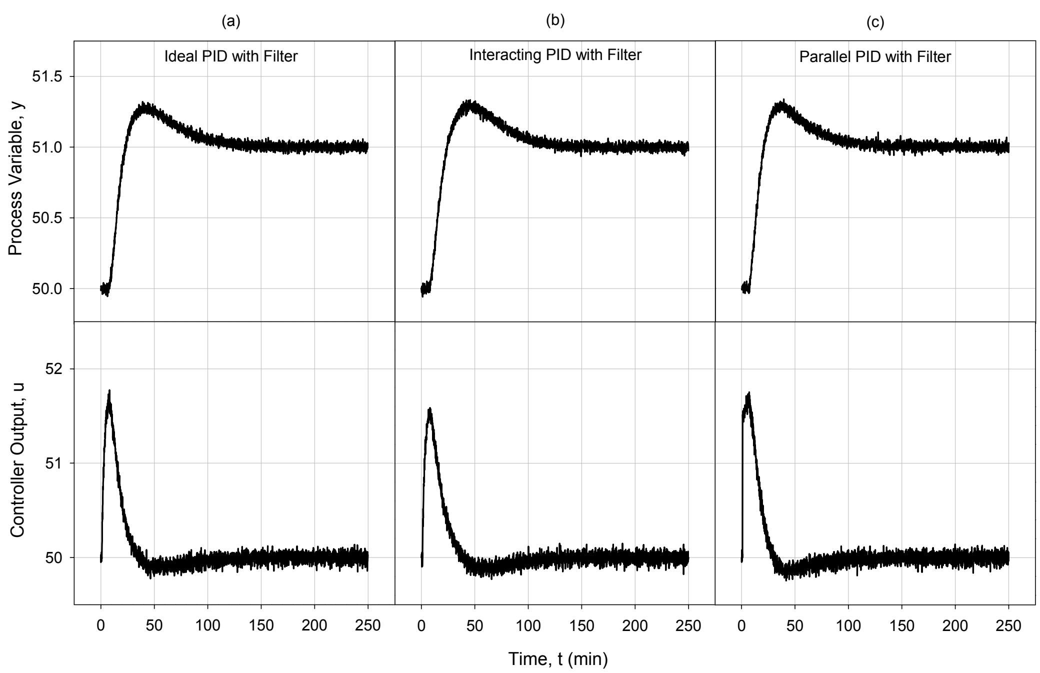

Figure 13. PID with Filter Controllers using Table 2 Tuning Parameters

In Fig. 13, notice how the Ideal (a), Interacting (b), and Parallel (c) perform similarly as they did in Fig. 9 for Example 1. The slight differences observed are expected due to the random noise added.

CONCLUSIONS

As demonstrated by Examples 1 and 2, signal filters improve controller performance by reducing the impact of noise in the measured process variable. Such filtering may be accomplished using an available industrial four-mode PID with Filter controller. If such a four-mode controller is unavailable, a three-mode PID controller may be combined with an external filter on either the controller output signal or the process variable measurement signal to form an effective four-mode PID with Filter controller. Therefore, the tuning correlations for the PID with Filter controller may be used to specify both the tunings for the PID controller and the time constant for the external first order filter.

This paper introduces IMC tuning correlations for the Parallel form of the PID with Filter controller for use with non-self regulating processes. The Parallel form of the PID with Filter controller consists of a system of two ODEs while the Ideal and Parallel forms consist of a single ODE. Therefore, the Parallel form is fundamentally different from the Ideal and Interacting forms. While IMC tuning correlations for the Ideal and Interacting forms exist [1], it is necessary to derive IMC tuning correlations for the Parallel form because it is fundamentally different.

The IMC tuning correlations for the Parallel form of the PID with Filter controller for use with non-self regulating processes show both similarities and differences with the IMC tuning correlations for the Ideal and Interacting forms. The controller gain, K_C, and reset time, τ_I, values calculated for the Parallel form differ little from those for the Ideal form. The derivative time, τ_D, and filter parameter, α, values calculated for the Parallel form differ increasingly from those for the Ideal form as the closed loop time constant, τ_{CL}, increases and the controller tuning becomes more conservative. These tuning correlations for the Parallel form are important because they confirm both similarities and differences with the fundamentally different Ideal form.

Generally, the choice between the Ideal, Interacting, and Parallel forms of the PID with Filter controller is dictated by the form of the industrial controller available. If there is an opportunity to select the form of the controller, the Parallel form has some benefit in that it filters only the contribution of the derivative term while leaving the proportional term that drives the controller action unfiltered.

NOMENCLATURE

$u(t)$, $U(s)$	Controller Output (in time and Laplace domains, respectively)
$y(t)$, $Y(s)$	Measured Process Variable
$y_{SP}(t)$, $Y_{SP}(s)$	Set Point
$e(t)$, $E(s)$	Error [$e(t) = y_{SP}(t) - y(t)$, $E(s) = Y_{SP}(s) - Y(s)$]
K_C	Controller Gain [u/y]
τ_I	Reset Time [time]
τ_D	Derivative Time [time]
α	Filter Parameter
τ_{CL}	Closed Loop Time Constant [time]

K_P^*	Integrator Gain [y/(u·time)]
θ_P	Dead Time [time]

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