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Design of Measurement Noise Filters for PID Control ⋆

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Abstract: This paper treats the trade-off between robustness, load disturbance attenuation, and measurement noise injection for PI and PID control using Lambda, SIMC, and AMIGO tuning. The effects of measurement noise are characterized by SDU, which is a measure of noise activity analogous to the IAE commonly used to characterize performance of load disturbance response. Simple design rules to choose the filter time constant for PI and PID controllers are also given for the three tuning methods.

Keywords: Measurement noise, filtering, trade-offs, PID control, performance, robustness.

1. INTRODUCTION

Most design methods do not take measurement noise explicitly into account. Instead, the filter time constant T_f is chosen by some empirical rule, for example as a fraction of the derivative time $T_f = T_d/N$. This simple approach has drawbacks as was pointed out in Isaksson and Graebe (2002). Methods like Åström and Hägglund (2005); Skogestad (2006) suggested how to detune the controllers to make the designs less noise sensitive. There are methods where both the controller parameters and the filter time constant are determined like Kristiansson and Lennartson (2006); Garpinger (2009); Sekara and Matausek (2009); Larsson and Hägglund (2011). These methods are complicated and require much apriori information.

In Romero Segovia et al. (2014) the design of noise filters for PID control was approached as a trade-off between load disturbance attenuation (IAE), measurement noise injection (SDU), and robustness (M_s, M_t). The measure SDU analogous to IAE was introduced to characterize measurement noise injection. The analysis was done for the design method AMIGO. In this paper the results are generalized to cover the popular design methods Lambda and SIMC, they are also compared with new results obtained for AMIGO. The results are summarized in simple design rules.

2. MODELS AND CRITERIA

The system shown in Figure 1 consists of the process and the controller. The process $P(s)$ is approximated by the FOTD model

$$P(s) = \frac{K}{1+sT}e^{-sL}, \tag{1}$$

where K, L, and T are the static gain, the apparent time delay, and the apparent time constant, respectively. These parameters can be obtained from a step response experiment. Process dynamics can be characterized by the

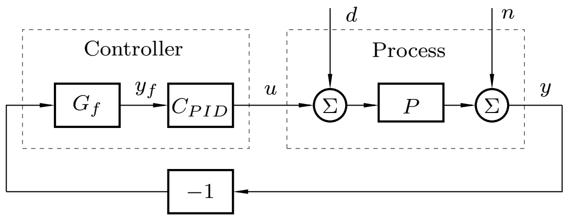

Figure 1. Block diagram of the system, y, y_f, are the measured and the filtered output, u is the control signal, d the load disturbance and n the measurement noise.

normalized time delay $\tau = L/(L+T)$, which has the property $0 \leq \tau \leq 1$. Lag dominant processes have small values of τ, while delay dominant have values of τ closer to one. Processes in between are denoted balanced.

The PID controller has the transfer function

$$C_{PID}(s) = k_p\left(1 + \frac{1}{sT_i} + sT_d\right) = k_p + \frac{k_i}{s} + k_d s, \tag{2}$$

where k_p, T_i, and T_d are the proportional gain, integral time, and derivative time.

Measurement noise is reduced by the second order filter

$$G_f(s) = \frac{1}{1 + sT_f + s^2T_f^2/2}, \tag{3}$$

where T_f is the filter time constant. A second order filter is used to ensure roll-off in the PID controller as recommended in Åström and Hägglund (2005).

The combination of the controller and the filter transfer functions is denoted by

$$C(s) = C_{PID}(s)G_f(s). \tag{4}$$

Using this representation, ideal controllers can be designed for the augmented plant $P(s)G_f(s)$.

The criteria used for the analysis considers robustness and performance in terms of attenuation of load disturbances and measurement noise injection. Robustness to process uncertainty are captured by the maximum sensitivities M_s

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and M_t.

$$M_s = \max_\omega |S(i\omega)|, \qquad M_t = \max_\omega |T(i\omega)|, \tag{5}$$

where

$$S(s) = \frac{1}{1+P(s)C(s)}, \qquad T(s) = \frac{P(s)C(s)}{1+P(s)C(s)} \tag{6}$$

are the sensitivity functions. Reasonable values for the robustness margins are $M_s, M_t = 1.2 - 2$.

Attenuation of load disturbances, is described by the response of the closed loop system to a unit step load disturbance at the process input, thus

$$G_{yd}(s) = \frac{P(s)}{1+P(s)C(s)} = P(s)S(s), \tag{7}$$

and captured by the integrated absolute error IAE

$$\text{IAE} = \int_0^\infty |e(t)|dt, \tag{8}$$

where e is the control error due to a unit step load disturbance applied at the process input as shown in Fig. 1.

A drawback of using feedback is that measurement noise is injected into the system. It is typically dominated by high frequencies, and it generates undesirable motion of the actuators which cause wear and possible break down. It is assumed that measurement noise enters the system additively at the process output as shown in Figure 1.

The transfer function from measurement noise n to the control signal u is

$$G_{un} = C(s)S(s). \tag{9}$$

The variance of the controller output u generated by the measurement noise is given by

$$\sigma_u^2 = \int_{-\infty}^{\infty} |G_{un}(i\omega)|^2 \Phi(\omega) d\omega \tag{10}$$

where $\Phi(\omega)$ is the spectral density of the noise. Measurement noise injection is characterized by

$$\text{SDU} = \sigma_{uw} = \sqrt{\int_{-\infty}^{\infty} |G_{un}(i\omega)|^2 \Phi_0 d\omega} = ||G_{un}||_2 \tag{11}$$

which is the standard deviation of the control signal for white measurement noise at the process output with spectral density Φ_0. The SDU is the L_2 norm of the transfer function G_{un}.

The expressions (10) is complex because of the shapes of the transfer function G_{un} and the spectral density $\Phi(\omega)$. It is rare that detailed information about the spectral density is known.

It is useful to have approximations of the criteria. Neglecting the contribution from the integral part and observing that $S(s)$ is close to one at high frequencies, we get

$$G_{un} \approx \frac{k_d s + k_p}{1 + sT_f + s^2 T_f^2/2} \tag{12}$$

Using the approximation (12) the variance of the control signal u can be computed analytically from formulas in (Åström, 1970, Chapter 5.2), thus

$$\hat{\sigma}_{uw} = \sqrt{\pi \left(\frac{2k_d^2 + k_p^2 T_f^2}{2T_f^3} \right) \Phi_0}. \tag{13}$$

2.1 Filter Design

Adding a filter reduces the effects of measurement noise, but it also reduces robustness and deteriorates the response to load disturbances. A compromise is then to choose the filter so that the impact on robustness and performance is not too large.

The filter has a significant effect on the controller transfer function. For PI control proportional action tends to disappear when T_f approaches the integral time constant T_i, while for PID control the derivative action disappears when T_f approaches the derivative time constant T_d.

The choice of the filter time constant determines the magnitude of SDU. For tuning purposes the filter time constant can be related to integral time T_i and to derivative time T_d for PI and PID control respectively. However, from a design perspective it is more natural to relate the filter time constant to gain crossover frequency ω_{gc}. In this paper, we will use an iterative procedure. The filter time constant T_f will be chosen as

$$T_f = \frac{\alpha}{\omega_{gc}}. \tag{14}$$

Controllers with this filter time constant will be designed for different values of α. The value of α will be chosen as a trade-off between performance, robustness, and attenuation of measurement noise. For a given value of α, the design procedure is as follows

- Find the FOTD approximation of the process P.
- Select the controller parameters as functions of K, L, and T, such that requirements about performance and robustness are satisfied.
- Choose the filter time constant $T_f = \alpha/\omega_{gc}$.
- Repeat the procedure with P replaced by PG_f until convergence.

3. CRITERIA ASSESSMENT

This section presents the trade-offs between load disturbance attenuation, robustness, and measurement noise injection for different processes. The methodology was applied to a test batch given in Åström and Hägglund (2005), which includes processes with different dynamics encountered in process control.

The trade-offs are illustrated in Figure 2, where the robustness level curves are a function of the performance (IAE) and the standard deviation of the control signal (SDU). High performance in terms of a small IAE value can be obtained with low robustness and large control signal deviations SDU. High robustness can be obtained if the IAE and the SDU values are large. A small SDU value can be obtained if the robustness is low or if the IAE value is large.

The controller parameters are obtained using Lambda (Sell (1995)) and SIMC (Skogestad (2003); Grimholt and Skogestad (2013)) tuning, respectively. The selection of these tuning methods is due to their high application in industry, and because they are based on the FOTD model of the process. For comparison with results previously presented in Romero Segovia et al. (2013) the AMIGO (Åström and Hägglund (2005)) tuning method is also used.

Table 1. Controller parameters using Lambda, SIMC and AMIGO tuning.

		k_p	T_i	T_d	T_i'	T_d'	k_i	k_d	T_{cl}
Lambda	PI	$\frac{1}{K}\frac{T}{(L+T_{cl})}$	T				$\frac{k_p}{T_i}$		$L,T,3T$
	PID	$\frac{1}{K}\frac{L/2+T}{L/2+T_{cl}}$	$T\frac{L}{2}$	$\frac{TL}{L+2T}$			$\frac{k_p}{T_i}$	$\frac{k_p}{T_d}$	$L,T,3T$
SIMC	PI	$\frac{1}{K}\frac{(T+L/3)}{(T_{cl}+L)}$	$\min\{T+L/3,4(T_{cl}+L)\}$				$\frac{k_p}{T_i}$		L
	PID	$\frac{1}{3KT_i'}\frac{(3T_i'+L)}{(T_{cl}+L)}$	$T_i'+T_d'$	$\frac{T_d'}{1+T_d'/T_i'}$	$\min\{T,4(T_{cl}+L)\}$	$\frac{L}{3}$	$\frac{k_p}{T_i}$	$\frac{k_p}{T_d}$	$L/2$
AMIGO	PI	$\frac{0.15}{K}+\frac{T}{KL}(0.35-\frac{LT}{(L+T)^2})$	$0.35L+\frac{13LT^2}{T^2+12LT+7L^2}$				$\frac{k_p}{T_i}$		
	PID	$\frac{1}{K}(0.2+0.45\frac{T}{L})$	$L\frac{0.4L+0.8T}{L+0.1T}$	$\frac{0.5LT}{0.3L+T}$			$\frac{k_p}{T_i}$	$\frac{k_p}{T_d}$	

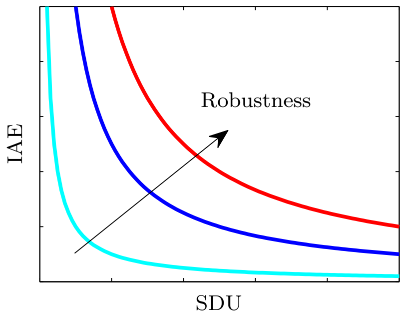

Figure 2. Trade-offs plot and relation with robustness.

Table 1 shows the tuning parameters for the different methods. The tuning parameter T_{cl}, the desired closed-loop time constant, varies between methodologies. For Lambda tuning $T_{cl} = T$ produces aggressive controllers, while $T_{cl} = 3T$ emphasizes robustness. To improve the attenuation of load disturbances for lag-dominated processes $T_{cl} = L$ is recommended. For the SIMC tuning, the recommended values for T_{cl} given in Skogestad (2003); Grimholt and Skogestad (2013) are used.

To illustrate the effects of the filter time constant T_f, three different processes are considered. The first process has the transfer function

$$P_1(s) = \frac{1}{(s+1)(0.1s+1)(0.01s+1)(0.001s+1)} \tag{15}$$

The FOTD approximation has $K = 1$, $T = 1.04$, $L = 0.08$, and $\tau = 0.07$ which shows the dominant lag dynamics of the process. Figure 3 shows the effects on performance and attenuation of measurement noise for the filter time constant given by (14) with α between 0 and 0.2. The results for $\alpha = 0.05$ are shown with squares for PI and triangles for PID. The results for PI and PID control are given in red and blue, respectively. The influence of filtering when using the AMIGO, SIMC, and Lambda tuning are shown in solid, dashed and dash-dotted lines, respectively. As expected heavier filtering attenuates measurement noise for all the tuning methods at the price of deteriorating the load disturbance response. This can be explained by the changes in process dynamics caused by filtering, which differ for each tuning method. Measurement noise attenuation is very similar for PID control when using AMIGO, SIMC and $\lambda = L$. Lower measurement noise injection can be achieved when using PI control for all the tuning methods, however, load disturbance attenuation deteriorates in contrast with PID control. The differences

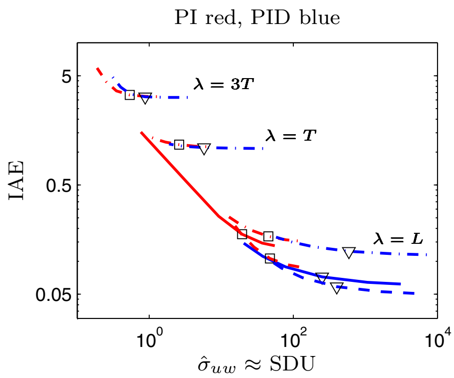

Figure 3. Trade-offs between performance and attenuation of measurement noise for the lag-dominated process P_1 for α values between 0 and 0.2.

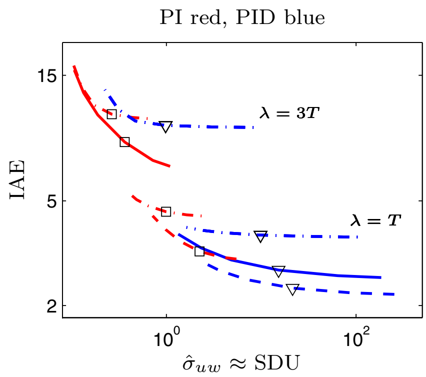

Figure 4. Trade-offs between performance and attenuation of measurement noise for the process P_2 with balanced dynamics for α values between 0 and 0.2.

in performance between the tuning methods is due to the robustness requirements. For AMIGO the limits are between 1.2 and 1.6, for Lambda and SIMC they are between 1.2 and 2. Thus, with higher robustness poor load disturbance attenuation can be anticipated (see Figure 2).

The second process has the transfer function

$$P_2(s) = \frac{1}{(s+1)^4} \tag{16}$$

The FOTD approximation has $K = 1$, $T = 2.92$, $L = 1.43$, and $\tau = 0.33$, which shows the balanced dynamics of the process. Figure 4 shows the trade-offs between performance and attenuation of measurement noise when filtering is used. Attenuation of measurement noise is quite

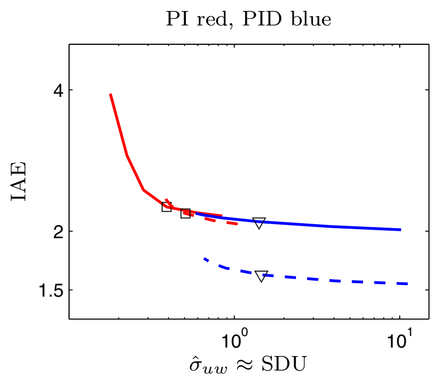

Figure 5. Trade-offs between performance and attenuation of measurement noise for the delay-dominated process P_3 for α values between 0 and 0.2.

similar for PID control when using AMIGO, SIMC and $\lambda = T$. Better noise rejection can be obtained for PID with $\lambda = 3T$ at the expense of losing in performance. If higher attenuation of measurement noise is required, PI control would be the right choice.

The last process considered has the transfer function

$$P_3(s) = \frac{1}{(0.05s+1)^2} e^{-s} \tag{17}$$

The FOTD approximation has $K = 1$, $T = 0.09$, $L = 1.01$, and $\tau = 0.92$, thus P_3 has delay dominant dynamics. Figure 5 shows the effects of filtering for the SIMC and the AMIGO tuning methods. For PID the same attenuation of measurement noise can be obtained, performance is not much affected by filtering. The differences in terms of performance is related to the robustness provided by each method, for this process AMIGO gives $1.42 \leq M_s \leq 1.52$, while SIMC gives $1.65 \leq M_s \leq 1.78$. For PI higher measurement noise attenuation is obtained with AMIGO, while better load disturbance attenuation are obtained with SIMC. The results for Lambda tuning are not shown in Figure 5, since the controllers obtained even without filtering ($\alpha = 0$) provide very poor robustness. This is also mentioned in Skogestad (2003); Garpinger and Hägglund (2012), where Lambda tuning is not recommended for delay-dominated processes due to the bad choice of the integral time constant.

Figures 3, 4 and 5 show that filtering has a significant effect on the trade-off between performance and measurement noise attenuation. Filtering changes the process dynamics, specially for higher values of α. Thus, the trade-off is governed by the design parameter α. A small value of α emphasizes performance, while a larger value emphasizes noise rejection. The choice of α is problem-dependent, the results obtained indicate that $\alpha = 0.05$ is a reasonable nominal value. The figures also show whether using PI or PID control can yield better results in terms of attenuation of load disturbance and measurement noise. Thus, when overlapping between the PI and PID curves occurs, which happens when the k_i parameters of the controllers are similar, there is no benefits in using PID since the filter time constant T_f reduces and even eliminates the effects of the derivative part of the controller.

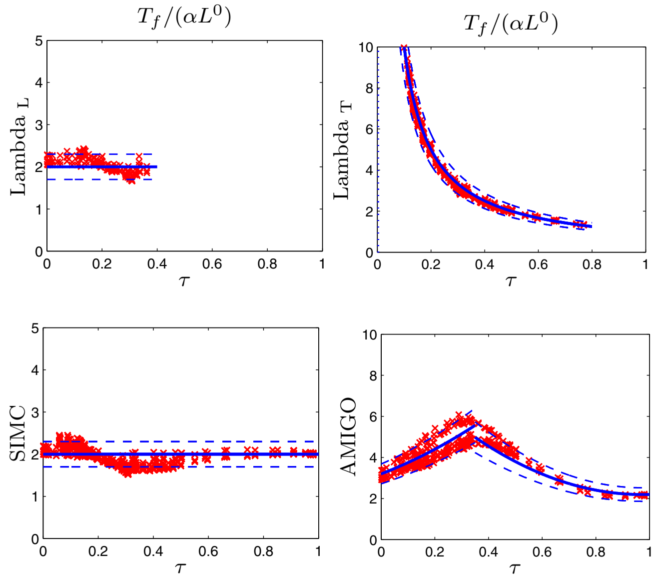

Figure 6. Filter time constant relations to FOTD model parameter L^0 for PI control using Lambda, SIMC and AMIGO tuning for $0 \leq \alpha \leq 0.05$.

4. DESIGN RULES

From a design point of view, it would be more useful to have simple design rules where no iteration is required, and which relate the filter time constant to the FOTD model of the original process, which is known, and the processes dynamics characterized by τ.

Figures 6 and 7 illustrate the relation between $T_f/(\alpha L^0)$, and τ for PI and PID control, where L^0 is the apparent time delay of the nominal process ($\alpha = 0$). The red markers in each plot correspond to the FOTD approximation of the 135 processes included in the Test Batch for $\alpha = 0.01$, 0.02, and 0.05, respectively. The blue solid lines correspond to the curve fitting carried out in each figure, and which equations are shown in Table 2. The blue dashed lines show the 15 percent variations of the equations. The vertical dotted blue lines in Figures 7 can be used as an indicator that shows that despite introduction of filtering, the characteristics of the PID controller are preserved. They indicate the value of τ for which the ratio $T_f/T_d^0 = 0.5$, where T_d^0 is the nominal derivative time, has been reached.

For the PI case, the left plots of Figure 6 show fairly similar outcomes for Lambda with $T_{cl} = L$ and SIMC. The functions are nearly constant and independent of τ. On the other hand, the results for Lambda with $T_{cl} = T$ and AMIGO depend on τ. For Lambda with $T_{cl} = T$ higher filter time constants are obtained for lag-dominated processes ($\tau < 0.2$), which is expected considering the poor performance (smaller ω_{gc}) provided by this design. For AMIGO the scaling with α produces two red curves since the values obtained for $\alpha = 0.05$ are above the other ones. The filter time constant does not change monotonically with τ due to the fact that AMIGO gives a proportional gain k_p for PI control that is too low for τ in the range of 0.3 to 0.6, see (Åström and Hägglund, 2005, Figure 7.1).

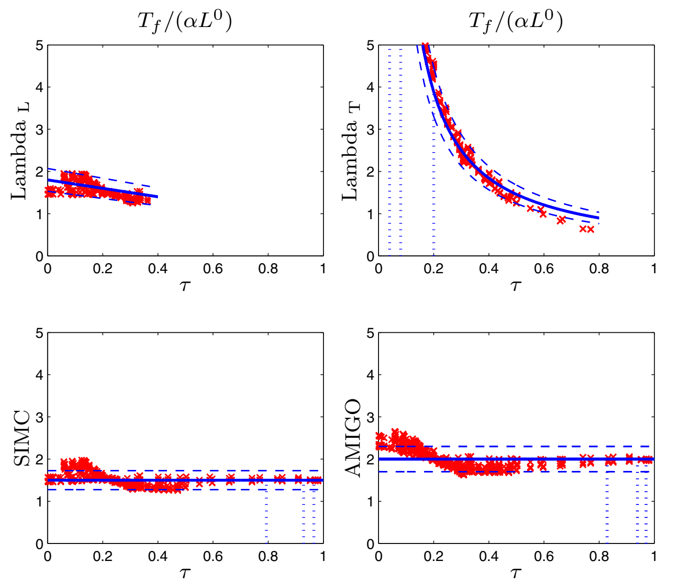

Figure 7. Filter time constant relations to FOTD model parameter L^0 for PID control using Lambda, SIMC and AMIGO tuning for $0 \leq \alpha \leq 0.05$.

Table 2. Simple design rules for the filter time constant T_f.

		T_{cl}	$T_f/(\alpha L^0)$
Lambda	PI	L	2
		T	$1/\tau$
	PID	L	$1.8 - \tau$
		T	$0.7/(\tau - 0.02)$
SIMC	PI	L	2
	PID	$L/2$	1.5
AMIGO	PI		$5\tau^2 + 5\tau + 3.2$, for $\tau < 0.35$
			$7.2\tau^2 - 14\tau + 9$, for $\tau \geq 0.35$
	PID		2

For the PID case, Figure 7 shows that despite the differences between the AMIGO and SIMC design methods, the similarities are quite remarkable. Notice that the filter time constant does not depend on τ. On the other hand, for Lambda tuning, the filter time constant depends on the dynamics of the process. The results show that for Lambda with $T_{cl} = L$, moderate filtering is used, while for $T_{cl} = T$ higher filter time constants are obtained for processes with lag dynamics.

Design rules for the filter time constant can be obtained applying curve fitting in the different curves for the PI and PID cases. The results are shown in Table 2. The rules for PI and PID control using AMIGO are applicable to all the processes in the Test Batch, the same holds for PI control using SIMC. Special cases are the ones for PI and PID control with Lambda, and PI control using SIMC tuning, which can be used for almost all the processes in the Test Batch, except the ones with integrating dynamics (process P_6). The rules given in Table 2 provide a good estimation within ±15%.

Based on the results of Table 2, the design of measurement noise filters can be described as follows:

- Obtain the FOTD approximation of the original process $P(s)$, this provides the values of L^0, T^0 and τ.
- Choose the value of the design parameter α between 0.01 and 0.05.
- Select a tuning method and calculate the filter time constant T_f using Table 2.
- Replace the process $P(s)$ by $P(s)G_f(s)$ and find the new FOTD model, which can be used to recalculate the controller parameters using Table 1.

5. EXAMPLE

The design method will be illustrated by applying it to the lag-dominated process $P_1(s)$ given by (15). To evaluate the effects of filtering in the system when using PID control, the different tuning methods are used, for Lambda the tuning parameter is chosen as $T_{cl} = L$. Following the steps described in Section 4, the filter time constant for each of the methods is calculated using the design rules for PID control given in Table 2. The controller parameters are then calculated using the FOTD approximation of $P_1(s)G_f(s)$ and the tuning rules given in Table 1.

Table 3 shows the effect of the filter time constant on the process and the controller parameters, as well as in the performance (IAE), stability, robustness (M_s, M_t) and noise attenuation ($\hat{\sigma}_{uw} \approx$ SDU). For comparison, the results are shown for $\alpha = 0$ (no filtering), and for the recommended value $\alpha = 0.05$. As expected, the use of filtering produces changes in process dynamics, where the dynamics of the filter add to the apparent time delay. The changes in the controller parameters depend on the design method. Filtering increases the attenuation of measurement noise while decreasing performance, nevertheless, the losses in performance are not significant for $\alpha = 0.05$ as can also be seen in Figure 3. The effects of filtering in robustness and stability are also method dependent, but they are connected to the process dynamic changes.

For completeness, Figure 8 also shows the effects on performance, robustness and attenuation of measurement noise of the filter time constant for the tuning methods. The top left plot shows the process output response to a unit step load disturbance. The top right shows Nyquist plots of the loop transfer function $G_l = P_1 C$ and the region where the sensitivity M_s is in the range $1.2 \leq M_s \leq 1.6$. The bottom left figure shows the magnitude of the transfer function from measurement noise to control signal G_{un}. The lower right figure shows the gain curve of G_l. The figure shows that for $\alpha = 0.05$ better performance can be obtained when using SIMC, while higher attenuation of measurement noise is provided by AMIGO. Robustness is within desired limits for the three methods. For this particular process, no big differences exist in the gain crossover frequency obtained with each of the methods.

6. SUMMARY

Filtering of measurement signals in PID control has been investigated in order to obtain insight and design rules. A second order Butterworth filter with a filter time constant T_f has been used to filter the measured signal. The effect of the filter time constant on performance, robustness, and

Table 3. Parameter dependence on the filter time constant for a process with lag-dominated dynamics using PID control

	α	τ	L	T	k_p	k_i	k_d	T_f	ω_{gc}	IAE	φ_m	g_m	M_s	M_t	$\hat{\sigma}_{uw}$
Lambda	0	0.067	0.075	1.040	9.58	8.89	0.35	0	7.61	0.113	64.15	260	1.21	1.02	∞
	0.05	0.072	0.081	1.036	8.88	8.25	0.35	0.006	7.20	0.121	63.88	38.21	1.23	1.01	1457
SIMC	0	0.067	0.075	1.040	9.76	20.54	0.23	0	7.66	0.048	49.82	312	1.41	1.24	∞
	0.05	0.072	0.081	1.036	9.02	17.62	0.23	0.006	7.25	0.057	50.18	43.63	1.42	1.22	978
AMIGO	0	0.067	0.075	1.040	6.44	17.83	0.24	0	5.69	0.059	51.22	381	1.30	1.28	∞
	0.05	0.074	0.083	1.036	5.84	15.25	0.24	0.008	5.28	0.069	51.55	44.3	1.30	1.27	649

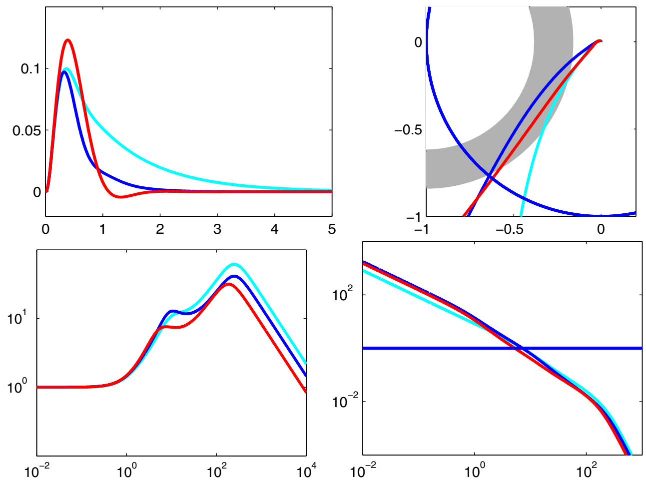

Figure 8. Dependence of performance, robustness and attenuation of measurement noise on the filter time constant for process $P_1(s)$ using PID control. The controllers are designed using the Lambda (cyan), SIMC (blue), and AMIGO (red) tuning methods. Table 2 is used to calculate T_f for $\alpha = 0.05$.

noise attenuation has been explored. Performance has been characterized by IAE and noise attenuation by the analog quantity SDU. Based on the FOTD model, tuning using Lambda, SIMC, and AMIGO has been investigated.

Insight into approximation of FOTD models has also been obtained. With the fitting methods used additional dynamics adds to the apparent time delay for lag-dominated processes and to the apparent time constant for delay-dominated processes.

The results have shown that filtering can significantly reduce the undesired control activity due to measurement noise, with only a moderate decrease of performance, and maintained robustness. This phenomenon is clearly seen in the trade-off figures presented in Section 3. The figures also show the effects of filtering on robustness for the different tuning methods.

Simple design rules for choosing the filter time constant for Lambda, SIMC, and AMIGO tuning are shown in Table 2. The rules are based on the FOTD parameters of the process (L^0, T^0), the normalized time delay τ, and the design parameter α. They are obtained by applying the iterative procedure to a test batch given in Åström and Hägglund (2005). The results have shown that a value of $\alpha = 0.05$ is a good trade-off between performance, robustness, and measurement noise attenuation.

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