Tuning rules for feedforward compensators combined with PID control

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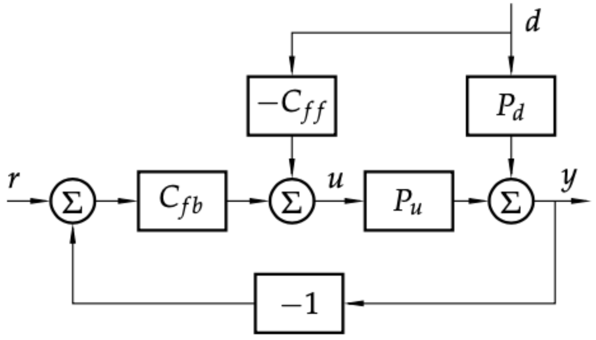
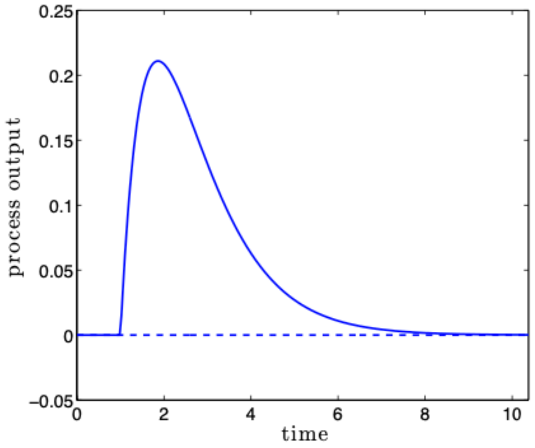
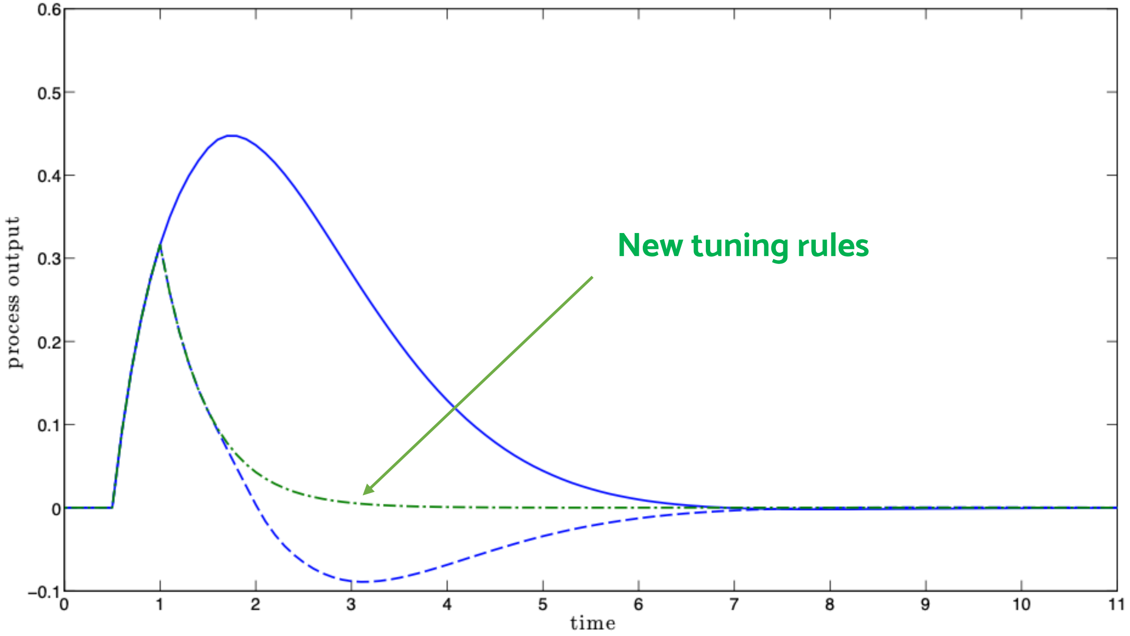
What will we see in this presentation?







Ideal compensation: $C_{ff} = \frac{P_d}{P_u} = P_d P_u^{-1}$

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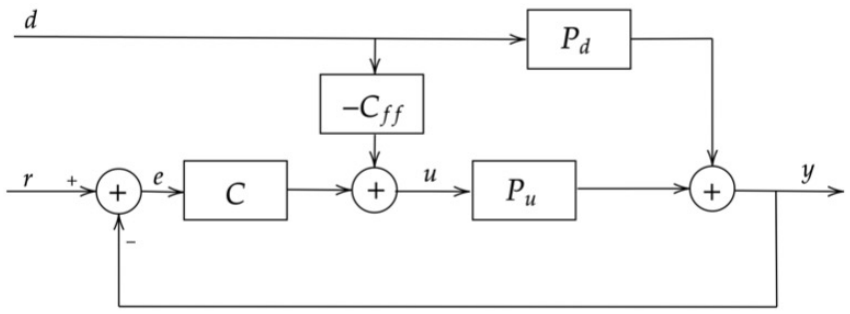

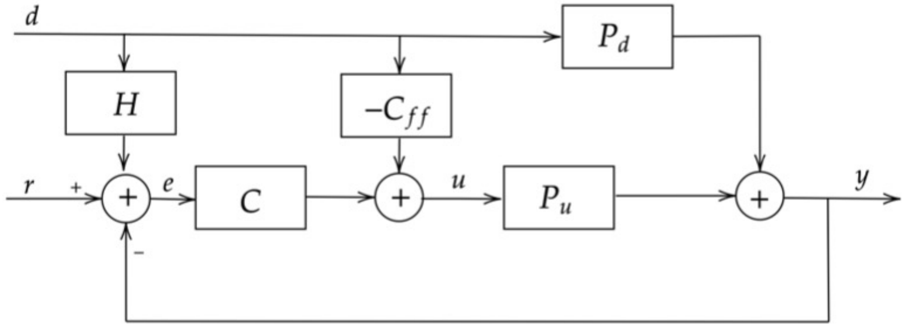

CS	Rule	M	$\mathbf{k_{ff}}$	$\mathbf{T_p}$	$\mathbf{T_z}$
C	1	OS	$(K_d/K_u)e^{(L_d-L_u)/T_d}$	T_d	T_u
C	2	OS	$\frac{K_d(T_u+\lambda)}{K_u(T_d+\lambda)})\epsilon \quad T_u \neq T_d$ $\frac{K_d}{K_u}e^{(L_d-L_u)/T_d} \quad T_u = T_d$ $\epsilon = e^{(L_u/(T_u+\lambda)-L_d/(T_d+\lambda))}$	–	–
C	3	OS	$K_d/K_u-(K/\tau_i)IE$	T_d	T_u
C	4	OS	$K_d/K_u-(K/\tau_i)IE$	$T_d-(L_u-L_d)/4$	T_u
C	5	IAE	$(K_d\,(T_d+L_d))/(K_u\,(T_d+L_u))$	T_d	T_u
C	6	IAE	$\frac{K_d(T_u+\lambda)}{K_u(T_d+\lambda)}\theta \quad T_u \neq T_d$ $\frac{K_d\,(T_d+L_d)}{K_u\,(T_d+L_u)} \quad T_u = T_d$ $\theta = e^{-(L_u-L_d+(T_u-T_d)\log(2))/(T_d+\lambda)}$	–	–
C	7	IAE	$K_d/K_u-(K/\tau_i)IE$	$T_d-(L_u-L_d)/1.7$	T_u
C	8	ISE	$(K_d/K_u)e^{-(L_u-L_d)/(\lambda+T_d)}$	T_d	T_u
C	9	ISE	$K_d/K_u-(K/\tau_i)IE$	$T_d-(L_u-L_d)/\alpha$ $\alpha = \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)}$	T_u
C	10	IAE ISE OS	$K_d/K_u-(K/\tau_i)IE$	$T_d-(L_u-L_d)/\alpha$ $\alpha = \begin{cases} \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)} & \text{ISE} \\ 1.7 & \text{IAE} \\ 4 & \text{OS} \end{cases}$	T_u
B	11	ISE	K_d/K_u	$\frac{3a-1-b+(a-1)\sqrt{1+4b}}{b-2}T_d \quad b<4a^2-2a$ or $b<a+\sqrt{a}$ $0 \quad$ otherwise $a = T_u/T_d$ $b = a(a+1)e^{L/T_d}$	$(T_p+T_u)\eta$ $\eta = \left(1-\frac{2T_u}{b(T_d+T_p)}\right)$
B	12	IAE ISE	K_d/K_u	$T_d-(L_u-L_d)/\alpha$ $\alpha = \begin{cases} \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)} & \text{ISE} \\ 1.7 & \text{IAE} \end{cases}$	T_u

$IE = K_d\,(L_u-L_d+T_u-T_d+T_p-T_z)$

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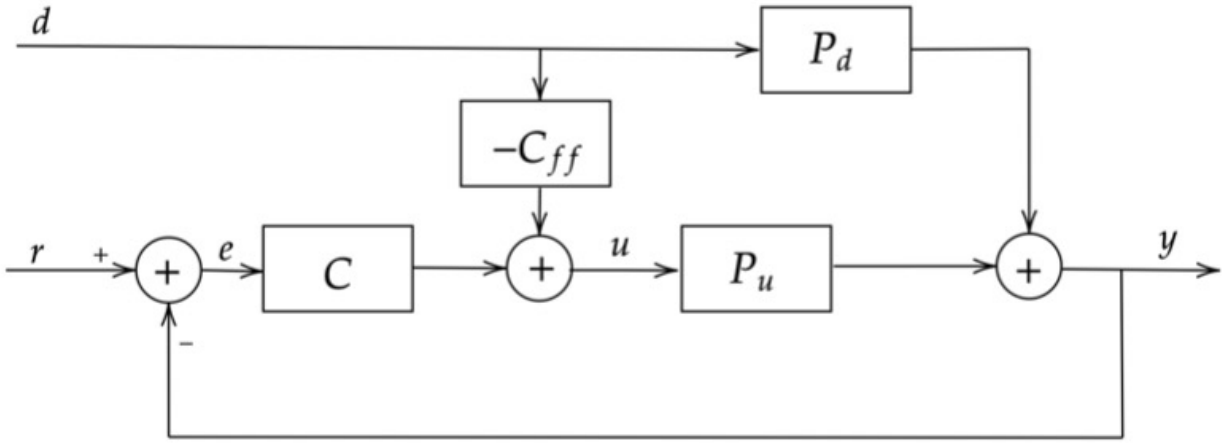
1 Preliminaries

Preliminaries



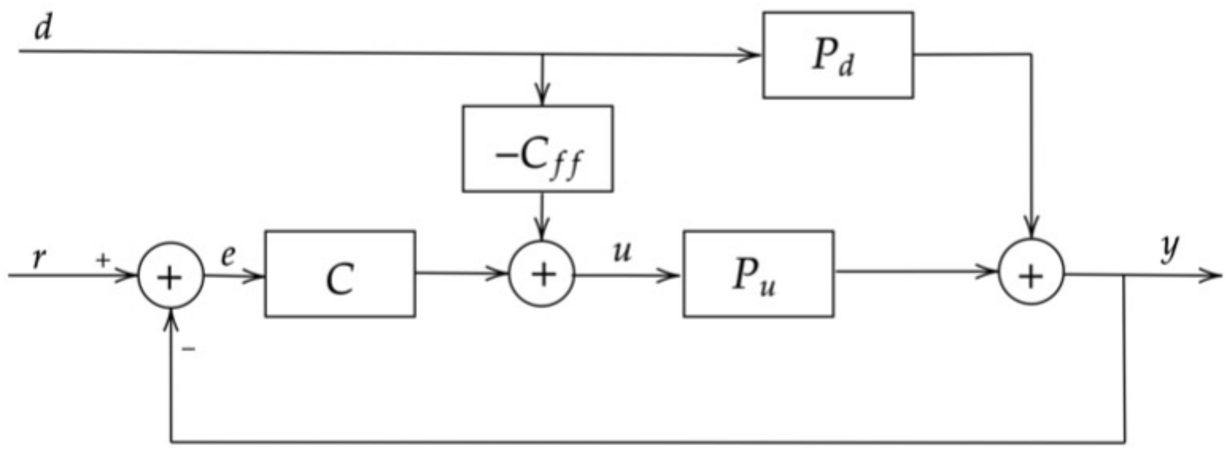
$$P_u = \frac{K_u}{1+sT_u}e^{-sL_u} \qquad P_d = \frac{K_d}{1+sT_d}e^{-sL_d}$$

$$K = \frac{T_u}{K_u(\lambda + L_u)}, \qquad \tau_i = T_u$$

$$C = K\left(1 + \frac{1}{s\tau_i}\right)$$

$$\lambda > (0.5 + \sqrt{2})L_u$$

Preliminaries



$$G_{y/d} = \frac{P_d - P_u C_{ff}}{1 + C P_u}$$

$$C_{ff} = k_{ff} \frac{sT_z + 1}{sT_p + 1} e^{-sL_{ff}}$$

$$C_{ff} = \frac{P_d}{P_u}$$

$$C_{ff} = \frac{K_d}{K_u} \frac{sT_u + 1}{sT_d + 1} e^{-s(L_d - L_u)}$$

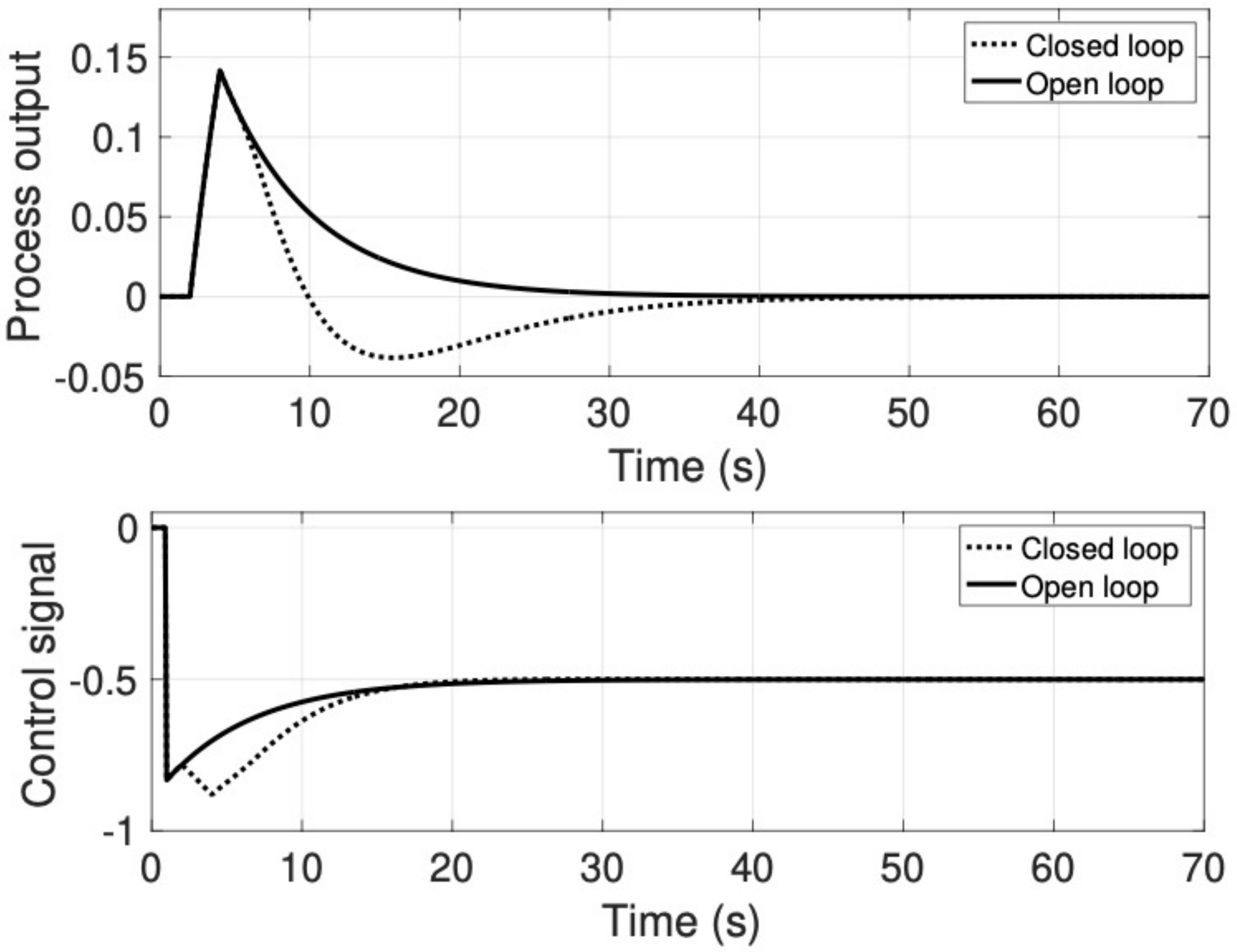
Preliminaries

$$P_u = \frac{1}{1+10s}e^{-3s}, \qquad P_d = \frac{0.5}{1+6s}e^{-s}$$

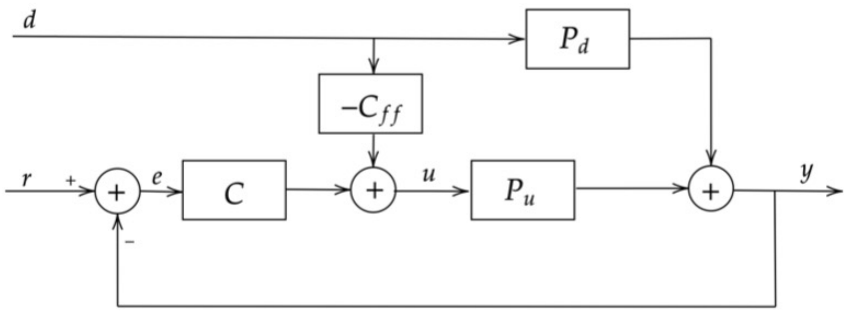
$$\tau_i = T_u = 10$$

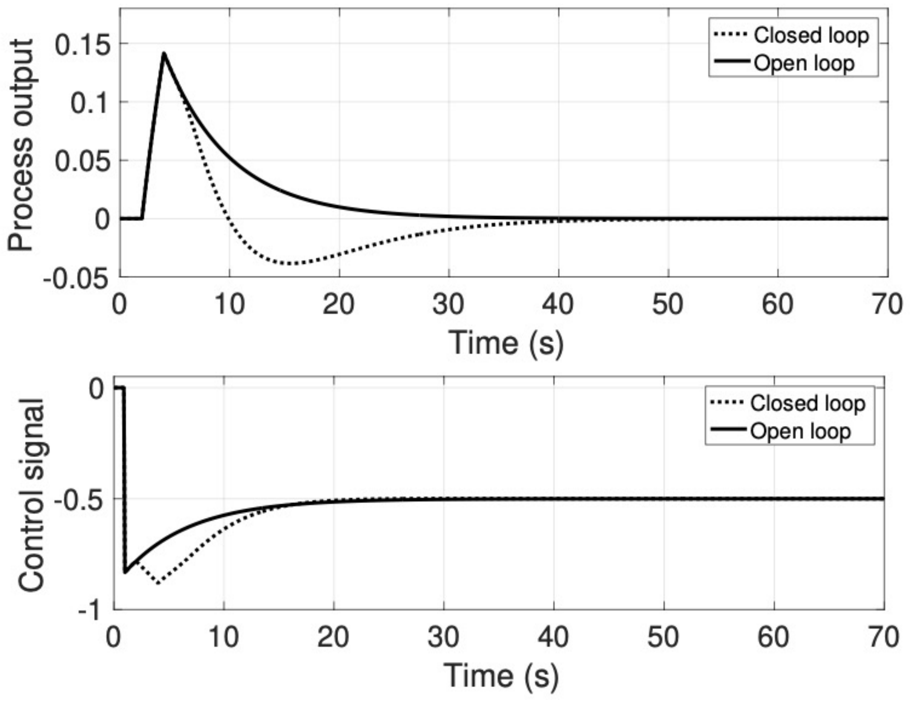
$$\lambda_2 = (0.5+\sqrt{2})L_u$$

$$C_{ff} = \frac{K_d}{K_u}\frac{sT_u+1}{sT_d+1}e^{-s(L_d-L_u)} = 0.5\frac{10s+1}{6s+1}$$



Preliminaries



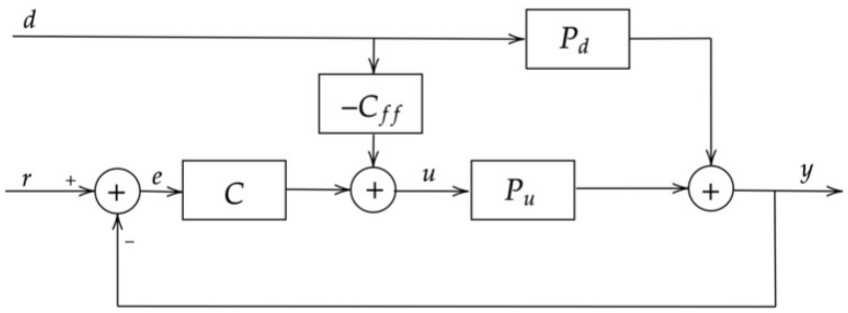


$$G_{y/d} = \frac{P_d - P_u C_{ff}}{1 + C P_u}$$

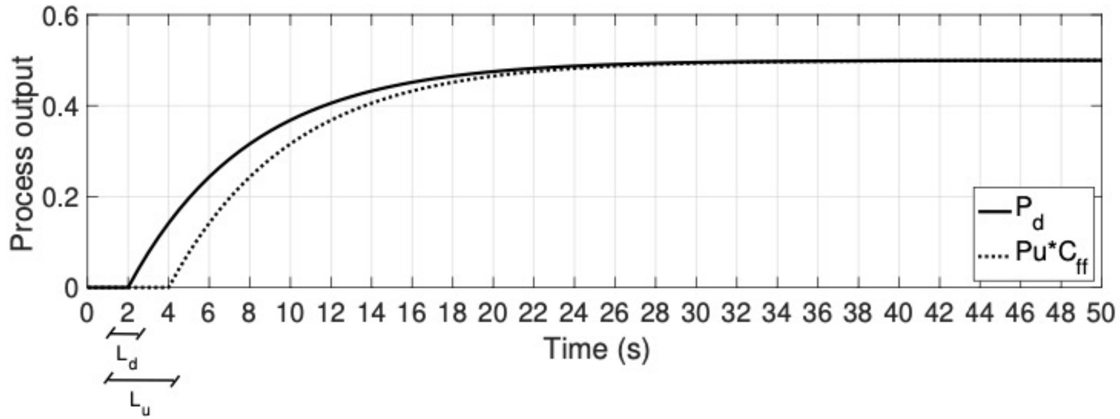
Residual term!

Feedback and feedforward interaction!

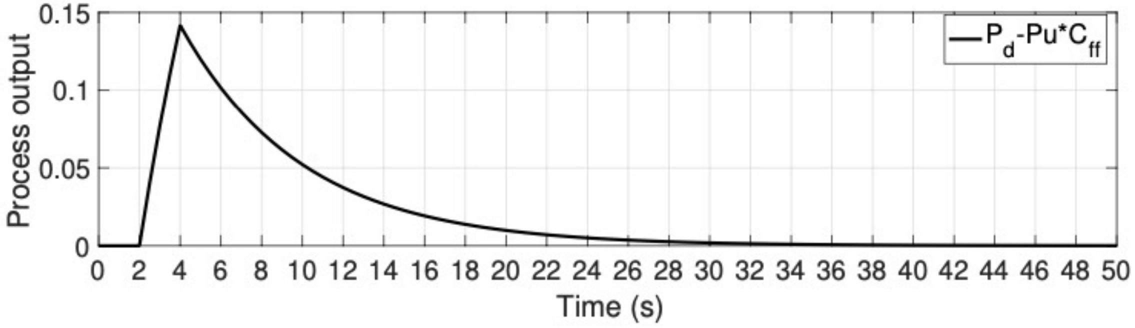
Preliminaries



$$G_{y/d} = \frac{P_d - P_u C_{ff}}{1 + C P_u}$$

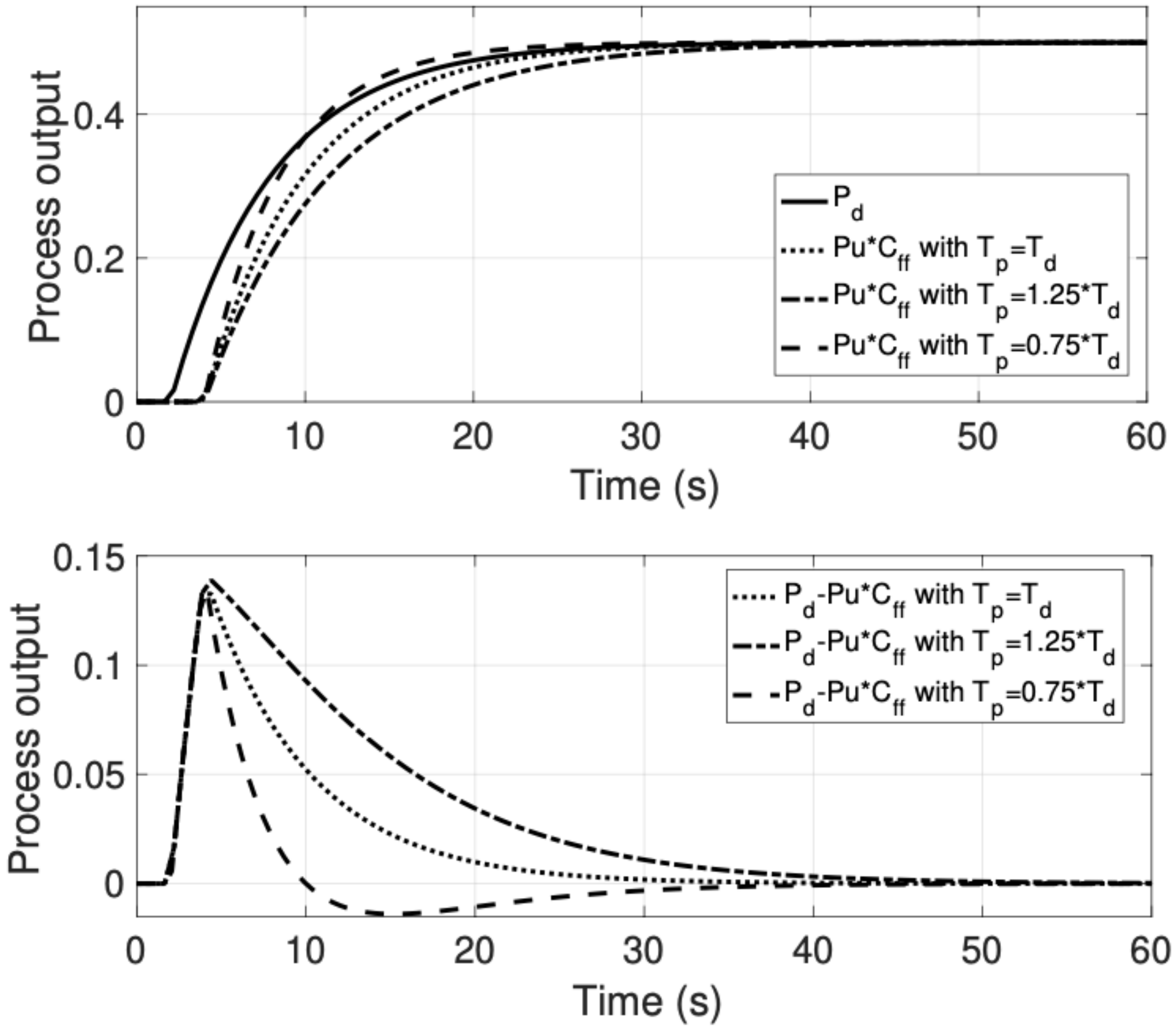


$$P_u = \frac{1}{1+10s} e^{-3s}, \qquad P_d = \frac{0.5}{1+6s} e^{-s}$$



$$C_{ff} = \frac{K_d}{K_u} \frac{sT_u + 1}{sT_d + 1} e^{-s(L_d - L_u)} = 0.5 \frac{10s+1}{6s+1}$$

Preliminaries



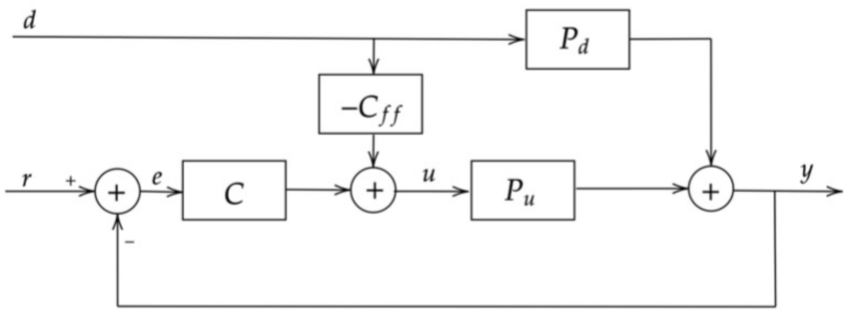
$$G_{ol} = P_d - P_u C_{ff}$$

There is room for improvment!

Preliminaries

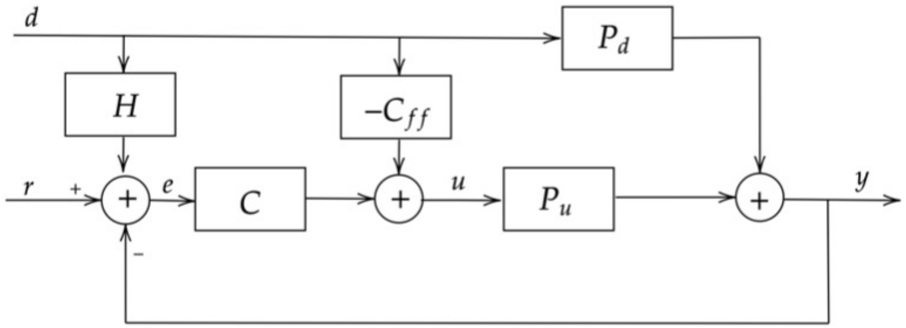
Classical solutions for inversion problems in industry?

Static feedforward



$$C_{ff} = k_{ff} = \frac{K_d}{K_u}$$

Non-interactive scheme



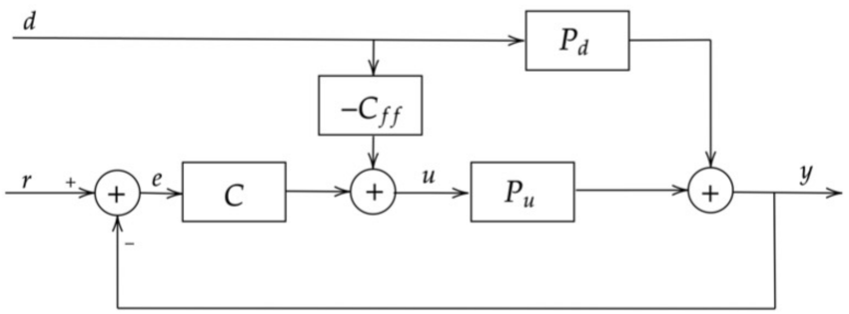
$$G_{e/d} = \frac{E(s)}{D(s)} = \frac{H - P_d + P_u C_{ff}}{1 + C P_u}$$

$$H = P_d - P_u C_{ff}$$

2 Tuning rules

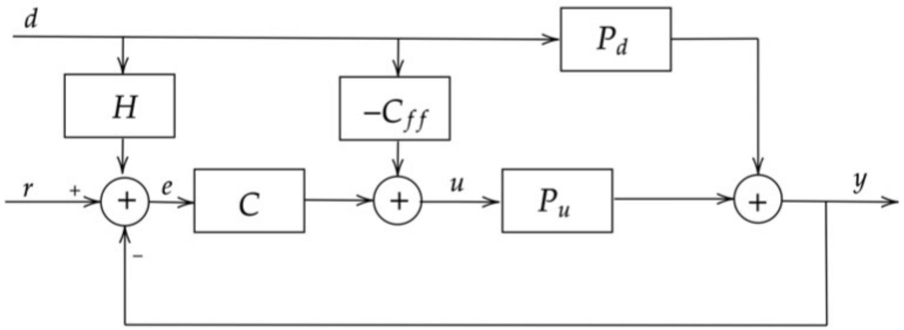
Tuning rules

Classical scheme



Use the classic feedforward control scheme and tune the feedforward compensator properly. This means that the feedback controller *C* must be taken into account in the design.

Non-interactive scheme



Use the non-interacting feedforward control scheme and tune the feedforward compensator properly. The design can be made without taking feedback controller *C* into account.

J. L. Guzmán, T. Hägglund. Tuning rules for feedforward control from measurable disturbances combined with PID control: A review. International Journal of Control, 2021.

Tuning rules

Inversion problems

- Non-realizable delay inversion.
- Right-half plane zeros.
- Integrating poles.

Tuning rule objective

- Minimize IAE.
- Minimize ISE.
- Reduce overshoot.

15 different tuning rules for feedforward compensators!

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Tuning rules

CS	Rule	M	k_{ff}	T_p	T_z
C	1	OS	$(K_d/K_u)e^{(L_d-L_u)/T_d}$	T_d	T_u
C	2	OS	$\frac{K_d(T_u+\lambda)}{K_u(T_d+\lambda)})\epsilon \quad T_u \neq T_d$ $\frac{K_d}{K_u}e^{(L_d-L_u)/T_d} \quad T_u = T_d$ $\epsilon = e^{(L_u/(T_u+\lambda)-L_d/(T_d+\lambda))}$	–	–
C	3	OS	$K_d/K_u - (K/\tau_i)IE$	T_d	T_u
C	4	OS	$K_d/K_u - (K/\tau_i)IE$	$T_d - (L_u - L_d)/4$	T_u
C	5	IAE	$(K_d\,(T_d+L_d))/(K_u\,(T_d+L_u))$	T_d	T_u
C	6	IAE	$\frac{K_d(T_u+\lambda)}{K_u(T_d+\lambda)}\theta \quad T_u \neq T_d$ $\frac{K_d\,(T_d+L_d)}{K_u\,(T_d+L_u)} \quad T_u = T_d$ $\theta = e^{-(L_u-L_d+(T_u-T_d)\log(2))/(T_d+\lambda)}$	–	–
C	7	IAE	$K_d/K_u - (K/\tau_i)IE$	$T_d - (L_u - L_d)/1.7$	T_u
C	8	ISE	$(K_d/K_u)e^{-(L_u-L_d)/(\lambda+T_d)}$	T_d	T_u
C	9	ISE	$K_d/K_u - (K/\tau_i)IE$	$T_d - (L_u - L_d)/\alpha$ $\alpha = \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)}$	T_u
C	10	IAE ISE OS	$K_d/K_u - (K/\tau_i)IE$	$T_d - (L_u - L_d)/\alpha$ $\alpha = \begin{cases} \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)} & \text{ISE} \\ 1.7 & \text{IAE} \\ 4 & \text{OS} \end{cases}$	T_u
B	11	ISE	K_d/K_u	$\frac{3a-1-b+(a-1)\sqrt{1+4b}}{b-2}T_d \quad b < 4a^2-2a$ or $b < a+\sqrt{a}$ $0 \quad$ otherwise $a = T_u/T_d$ $b = a(a+1)e^{L/T_d}$	$(T_p+T_u)\eta$ $\eta = \left(1 - \frac{2T_u}{b(T_d+T_p)}\right)$
B	12	IAE ISE	K_d/K_u	$T_d - (L_u - L_d)/\alpha$ $\alpha = \begin{cases} \frac{L}{2T_d\left(1-e^{-L/(2T_d)}\right)} & \text{ISE} \\ 1.7 & \text{IAE} \end{cases}$	T_u
$IE = K_d\,(L_u - L_d + T_u - T_d + T_p - T_z)$					

Static $C_{ff} = k_{ff}$

Lead – lag $C_{ff} = k_{ff}\dfrac{1+sT_z}{1+sT_p}$

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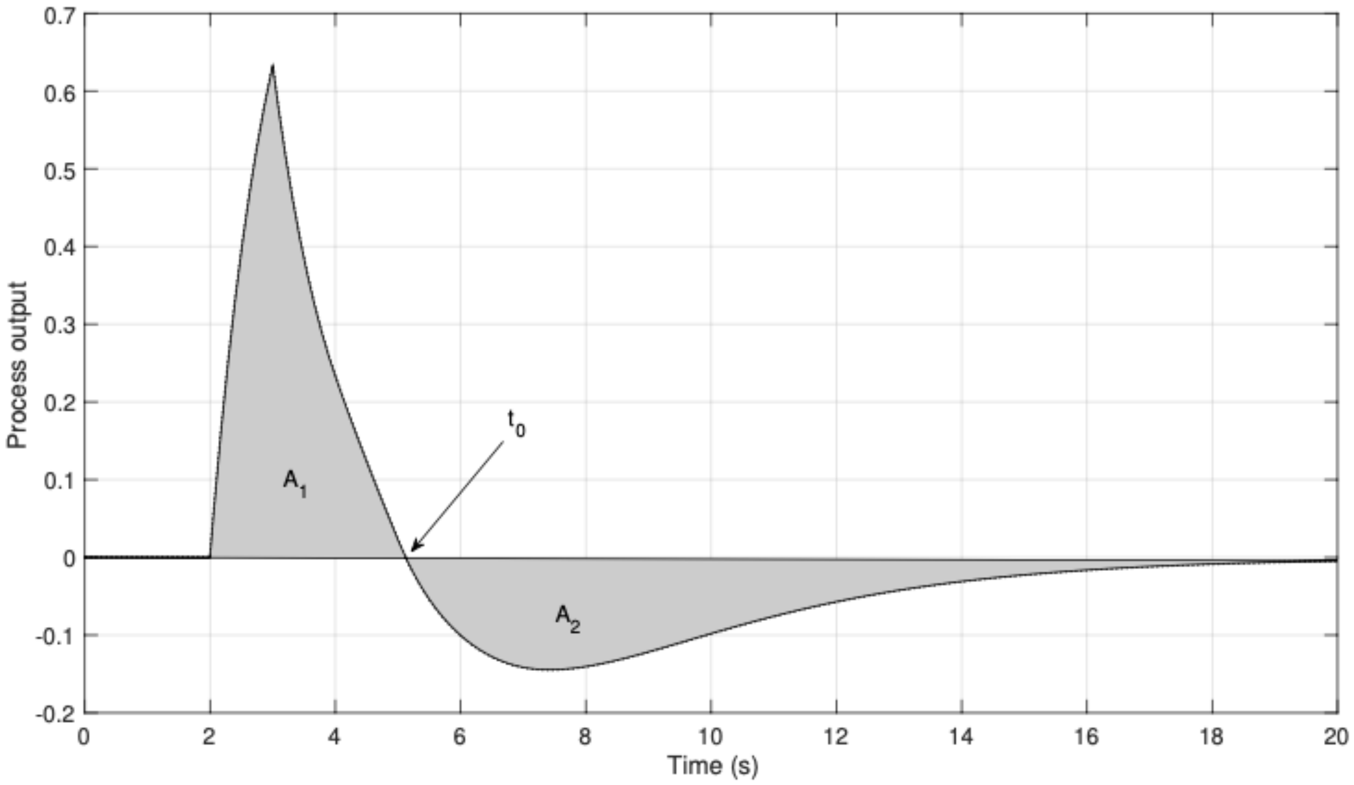
Tuning rules



$$IE = -\left(\lambda + L_u\right)\left(K_d - k_{ff} K_u\right)$$

$$IAE = 2|A_1|$$

$$IAE = \int_0^{\infty} |e(t)|dt = \int_0^{t_0} e(t)dt - \int_{t_0}^{\infty} e(t)dt$$

$$IAE = 2\int_0^{t_0} e(t)dt - IE_{+\infty}$$

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Tuning rules

$$P_{ff} = \frac{K_d e^{-sL_d}}{1+sT_d} - \frac{K_u e^{-sL_u}}{1+sT_u} C_{ff}$$

$$E(s) = G_{e/d}\frac{1}{s} = -(\lambda + L_u)\left(\frac{sK_d e^{-sL_d}}{(sT_d+1)(s\lambda+1)} - \frac{sC_{ff}K_u e^{-sL_u}}{(sT_u+1)(s\lambda+1)}\right)\frac{1}{s}$$

$$G_{ol} = \frac{Y}{D} = \underbrace{P_d - P_u C_{ff}}_{P_{ff}}$$

$$S = \frac{1}{1 + K\frac{1+s\tau_i}{s\tau_i}K_u\frac{1-sL_u}{sT_u+1}} = \frac{(\lambda+L_u)s}{\lambda s+1}$$

$$y_{ol}(t) = \begin{cases} 0 & : 0 \le t < L_d \\ K_d\left(1 - e^{(L_d-t)/T_d}\right)d & : L_d \le t < L_u \\ \mathcal{L}^{-1}\{P_{ff}D\} & : t \ge L_u \end{cases}$$

$$y_{e/d}(t) = \begin{cases} 0 & : 0 \le t < L_d \\ -\frac{K_d(\lambda+L_u)\left(e^{(L_d-t)/T_d}/T_d - e^{(L_d-t)/\lambda}/\lambda\right)}{\lambda - T_d}d & : L_d \le t < L_u \\ \mathcal{L}^{-1}\{P_{ff}SD\} & : t \ge L_u \end{cases}$$

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Tuning rules

Classical scheme

Rule 7 *Tuning rule for the classical control scheme to minimize IAE with a lead-lag compensator:*

1. *Set* $T_z = T_u$ *and* $L_{ff} = \max(0, L_d - L_u)$.
2. *Calculate* T_p *as:*

$$T_p = \begin{cases} T_d & L_u - L_d \le 0 \\ T_d - \dfrac{L_u - L_d}{1.7} & 0 < L_u - L_d < 1.7\,T_d \\ 0 & L_u - L_d > 1.7\,T_d \end{cases}$$

3. *Calculate the compensator gain* k_{ff} *as:*

$$k_{ff} = \frac{K_d}{K_u} - \frac{K}{\tau_i} IE$$

$$IE = \begin{cases} K_d\,(T_u - T_d + T_p - T_z) & L_d \ge L_u \\ K_d\,(L_u - L_d + T_u - T_d + T_p - T_z) & L_d < L_u \end{cases}$$

4. *End of design.*

Non-interactive scheme

Rule 12 *Tuning rule for the non-interacting control scheme to minimize ISE, IAE, or to remove the overshoot with a lead-lag compensator.*

1. *Set* $k_{ff} = K_d/K_u$, $T_z = T_u$ *and* $L_{ff} = \max(0, L_d - L_u)$.
2. *Calculate* $L = L_u - L_d$.
3. *Calculate* α *depending on the desired behaviour:*

$$\alpha = \begin{cases} \frac{L}{2\,T_d\left(1-e^{-L/(2T_d)}\right)} & \textit{aggressive (ISE minimization)} \\ 1.7 & \textit{moderate (IAE minimization)} \\ 4 & \textit{conservative (overshoot removal)} \end{cases}$$

4. *Set* T_p *according to:*

$$T_p = \begin{cases} T_d & L \le 0 \\ T_d - \frac{L}{\alpha} & 0 < L < \alpha\,T_d \\ 0 & L \ge \alpha\,T_d \end{cases}$$

   If $T_p = 0$, *select a value close to zero to obtain a realizable compensator.*

5. *Set* $H(s)$ *with Equation* (4.66) *for the non-interacting scheme.*
6. *End of design.*

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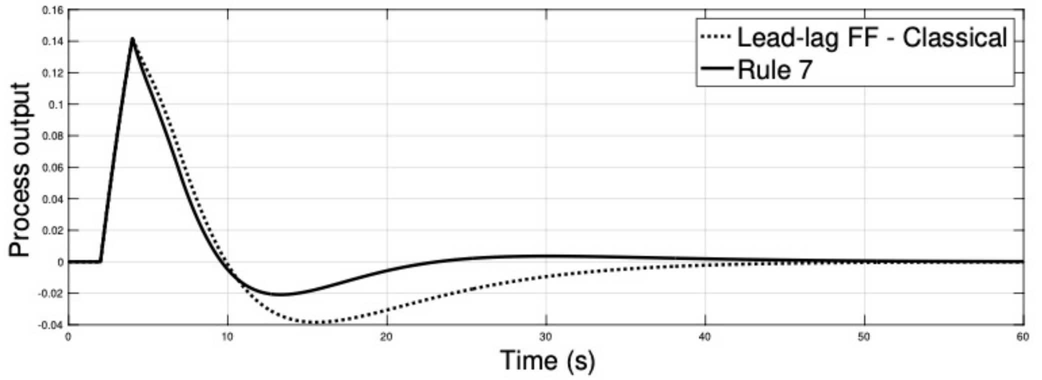
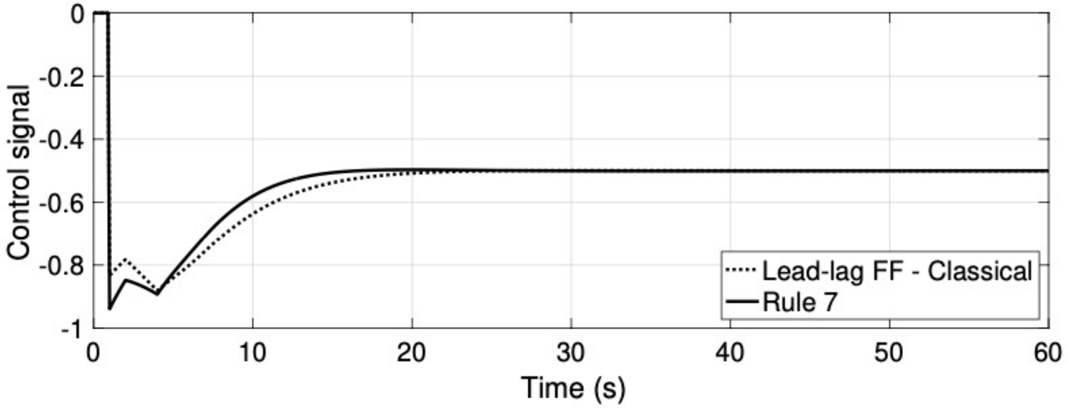
Tuning rules

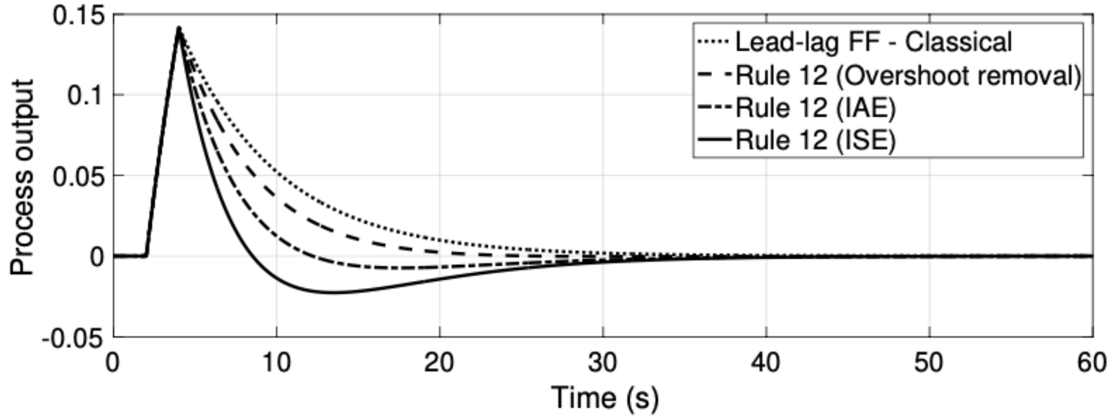
Classical scheme

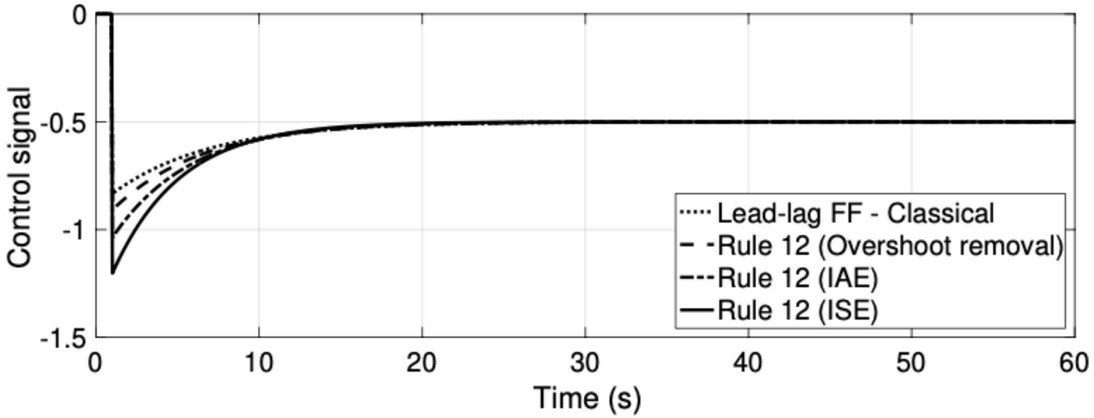




35% IAE reduction
45% Overshoot reduction

Non-interactive scheme



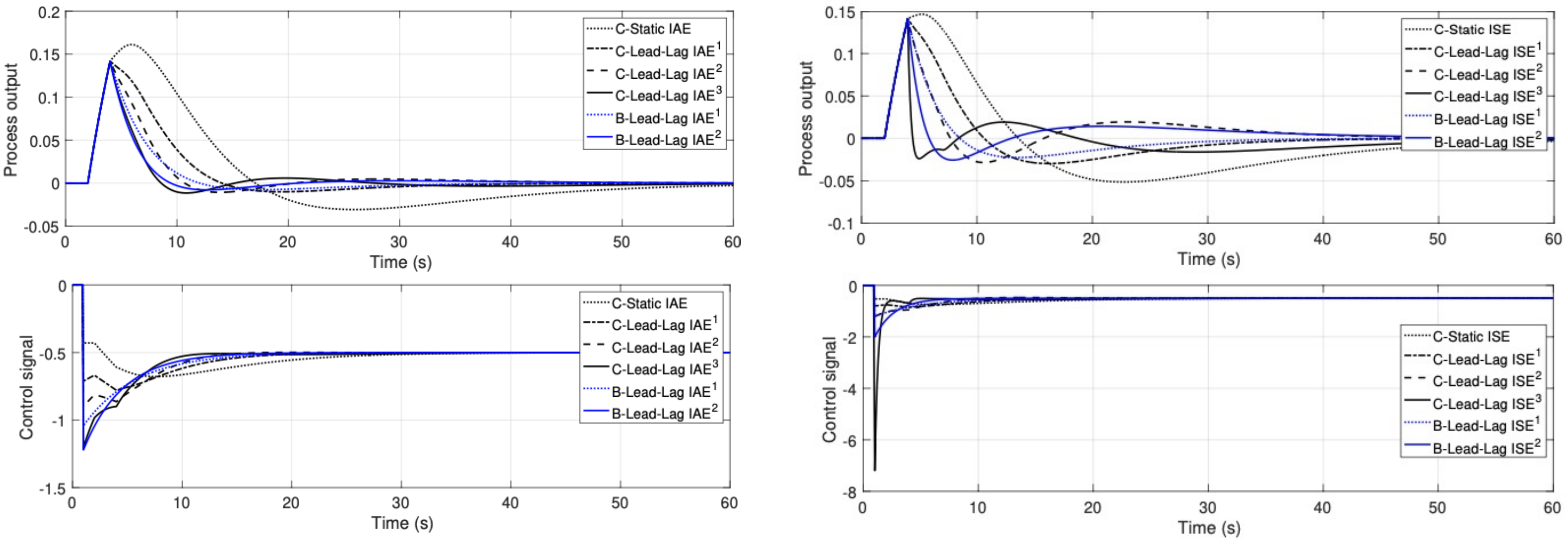


38% IAE reduction
47% ISE reduction

3 Selecting control schemes and tuning rules

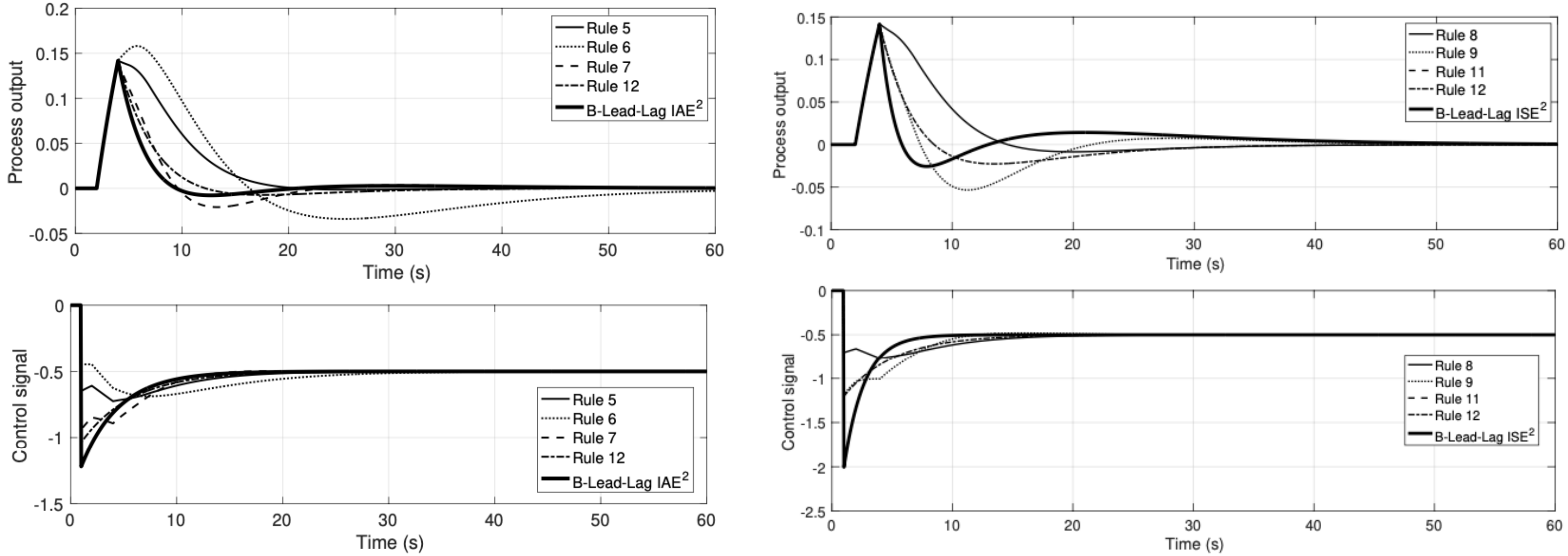
Selecting control scheme and tuning rules

Obtaining optimal tuning values



Selecting control scheme and tuning rules

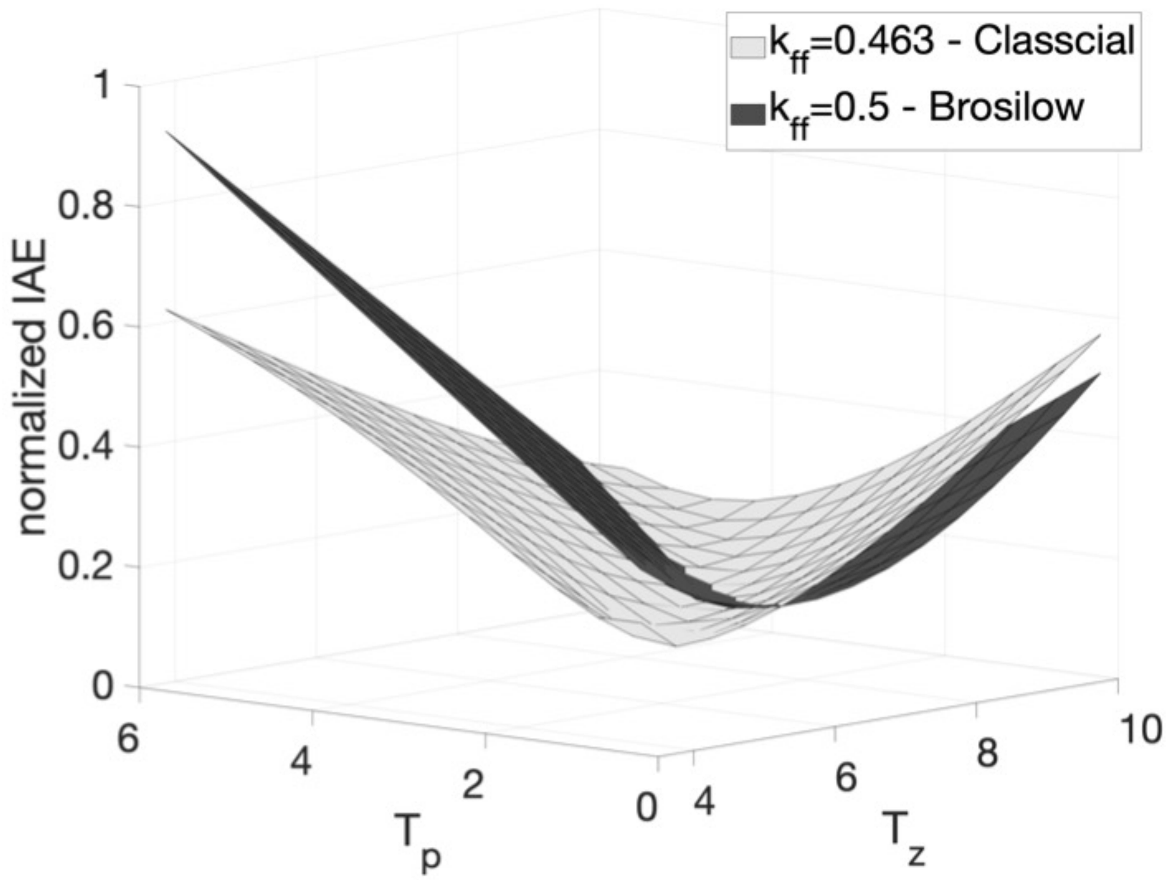
Comparing the rules with the optimal rule

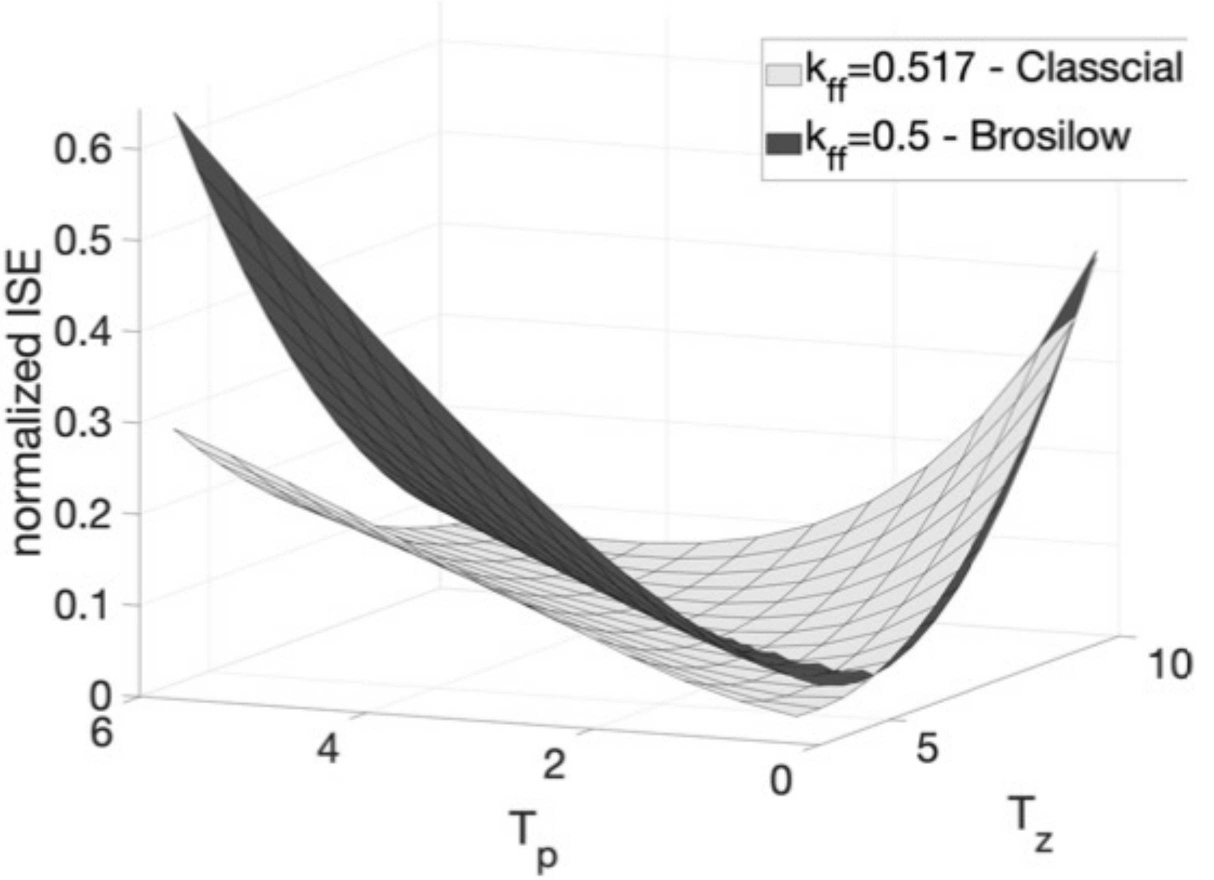


Selecting control scheme and tuning rules

Rules	IAE_{norm}	ISE_{norm}	overshoot	peak	k_{ff}	T_z	T_p
FB	1	1	0	9.57	–	–	–
Static	0.477	0.182	9.1	44.69	0.5	–	–
Lead-Lag	0.257	0.082	7.67	76.28	0.5	10	6
Rule 1	0.284	0.139	0	36.47	0.358	10	6
Rule 2	0.514	0.324	2.5	23.54	0.306	–	–
Rule 3	0.236	0.116	0.22	44.15	0.386	10	6
Rule 4	0.18	0.084	0.56	57.97	0.414	10	5.5
Rule 5	0.232	0.113	0.3	45.07	0.389	10	6
Rule 6	0.461	0.199	6.8	37.6	0.446	–	–
Rule 7	0.166	0.059	4.18	87.79	0.453	10	4.824
Rule 8	0.212	0.094	1.7	54.29	0.422	10	6
Rule 9	0.207	0.061	10.66	136.17	0.491	10	4.158
Rule 10 (OS)	0.18	0.084	0.56	57.97	0.414	10	5.5
Rule 10 (IAE)	0.166	0.059	4.18	87.79	0.453	10	4.824
Rule 10 (ISE)	0.207	0.061	10.66	136.17	0.491	10	4.158
Static	0.682	0.363	0	0	0.5	–	–
Lead-Lag	0.229	0.089	0	66.67	0.5	10	6
Rule 11	0.151	0.033	5.13	301.57	0.5	6.789	1.691
Rule 12 (OS)	0.174	0.07	0.06	81.82	0.5	10	5.5
Rule 12 (IAE)	0.143	0.053	1.46	107.32	0.5	10	4.824
Rule 12 (ISE)	0.16	0.047	4.53	140.51	0.5	10	4.158

Selecting control scheme and tuning rules





4 Performance indices

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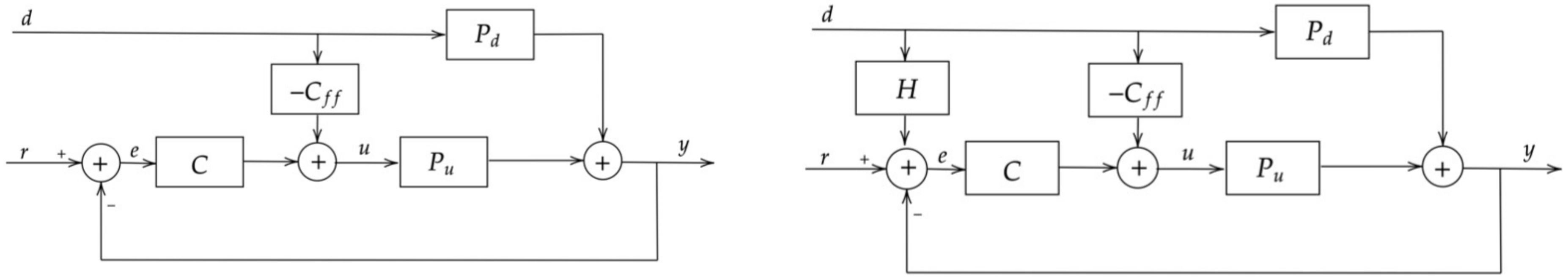
Performance indexes



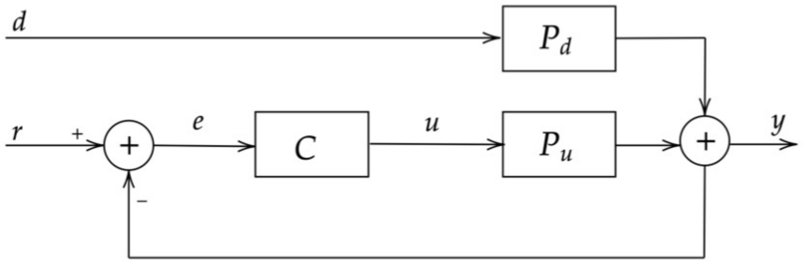
$$I_{FF/FB} = 1 - \frac{IAE_{FF}}{IAE_{FB}},$$

where IAE_{FB} is the integrated absolute value of the control error obtained when only feedback is used, and IAE_{FF} is the corresponding IAE value obtained when feedforward is added to the loop.

As long as the feedforward improves control, i.e. $IAE_{FF} < IAE_{FB}$, the index is in the region $0 < I_{FF/FB} < 1$.

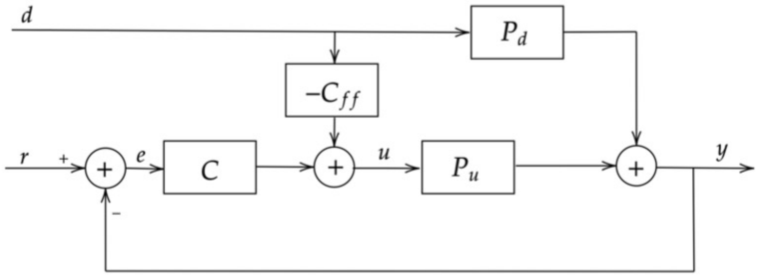
Performance indexes

$$IAE_{FB} = K_d(\lambda + L_u)d$$



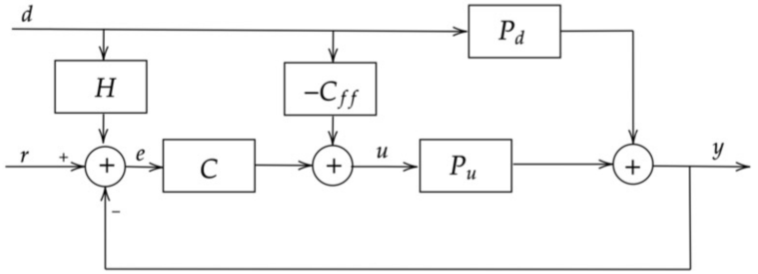
$$IAE_{FF} = K_d\left(L_1 - \tau\left(1 - 2e^{-L_1/\tau}\right)\right)d$$

$$\tau = T_d - T_p \text{ and } L_1 = \max(0, L_u - L_d)$$



$$IAE_{FF} = dK_d(L_u - L_d)$$

$$\alpha = 1 - \frac{1}{a} + \frac{2}{a}e^{-a}, \quad a = \frac{L_u - L_d}{T_d - T_u - T_p + T_z}$$



Performance indexes

Rules	IAE^r	IAE^e	$I^r_{FF/FB}$	$I^e_{FF/FB}$
FB	4.371	4.372	0	0
Static	2.116	1.549	0.516	0.646
Lead-lag	1.125	1.096	0.743	0.749
Rule 5	1.014	0.971	0.768	0.778
Rule 6	2.043	1.46	0.533	0.666
Rule 7	0.727	0.627	0.834	0.857
Lead-lag	1.0000	1.000	0.771	0.771
Rule 12	0.627	0.627	0.857	0.857

Performance indexes

$$\frac{IAE_{\text{classical}}}{IAE_{\text{noninteracting}}} = \frac{2(L_u + \lambda) f(\lambda / T_d)}{T_d}$$

$$f(\lambda/T_d) = \begin{cases} \left(\dfrac{\lambda}{T_d}\right)^{-\dfrac{\lambda}{\lambda - T_d}} & \lambda \neq T_d \\ e^{-1} & \lambda = T_d \end{cases}$$

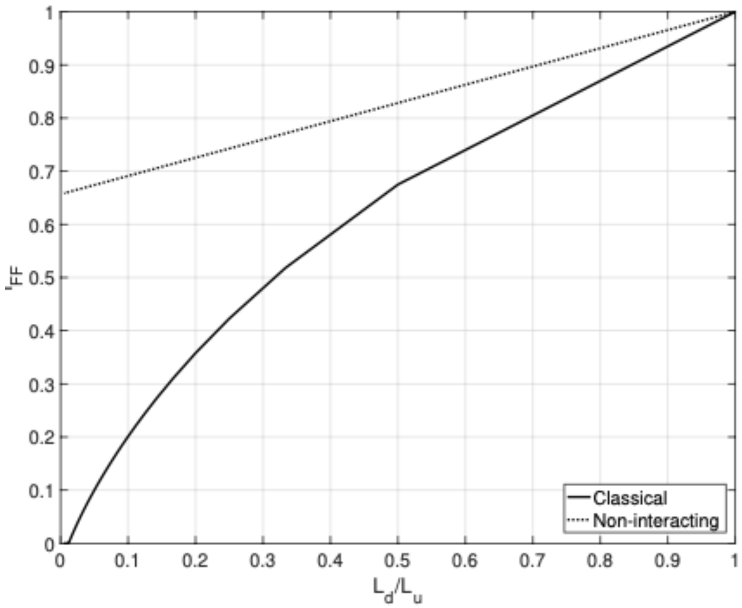
Therefore, the classical scheme gives a smaller IAE value when

$$T_d > 2(L_u + \lambda) f(\lambda / T_d)$$

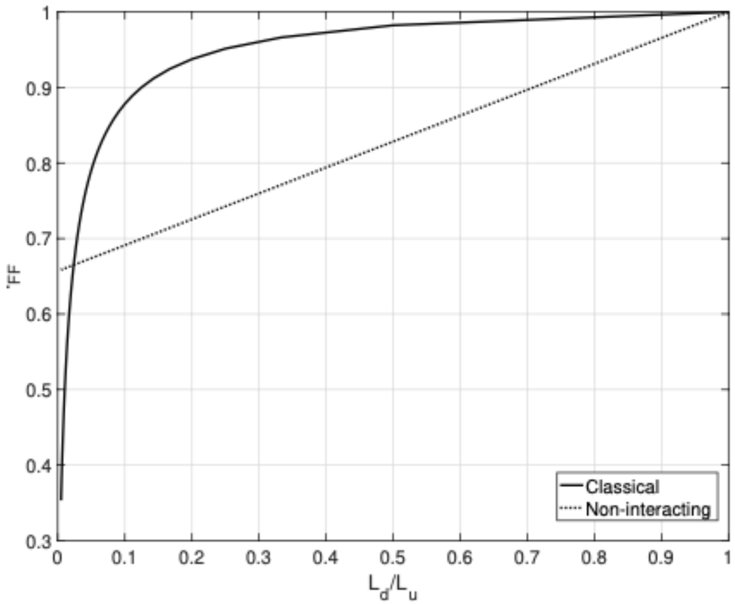
Since $0 < f(\lambda/\tau) \leq 1$, one can conclude that the classical scheme gives a better performance when T_d is large compared to process dead time L_u or the desired closed-loop time constant λ, i.e. when the load disturbance is varying slowly.

Performance indexes

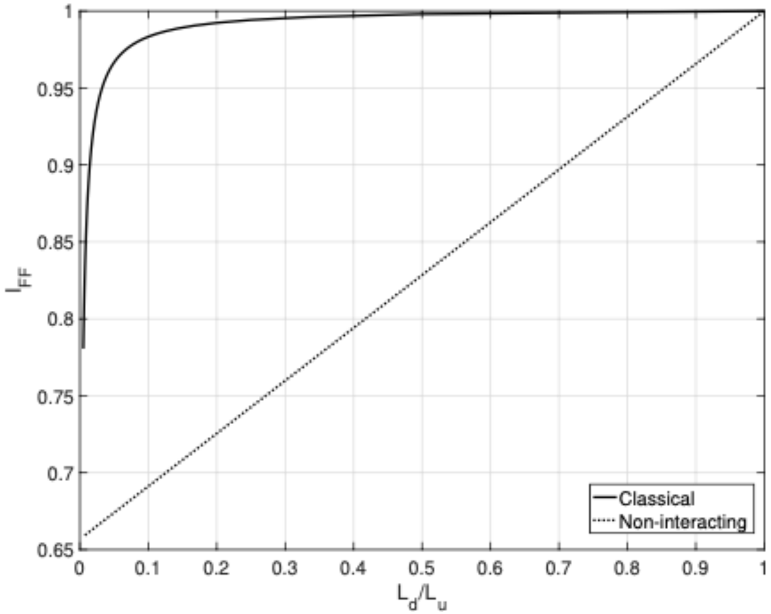
$$P_u = \frac{1}{1+10s}e^{-L_u s}, \qquad P_d = \frac{1}{1+T_d s}e^{-0.1s}$$



$T_d = 0.1$



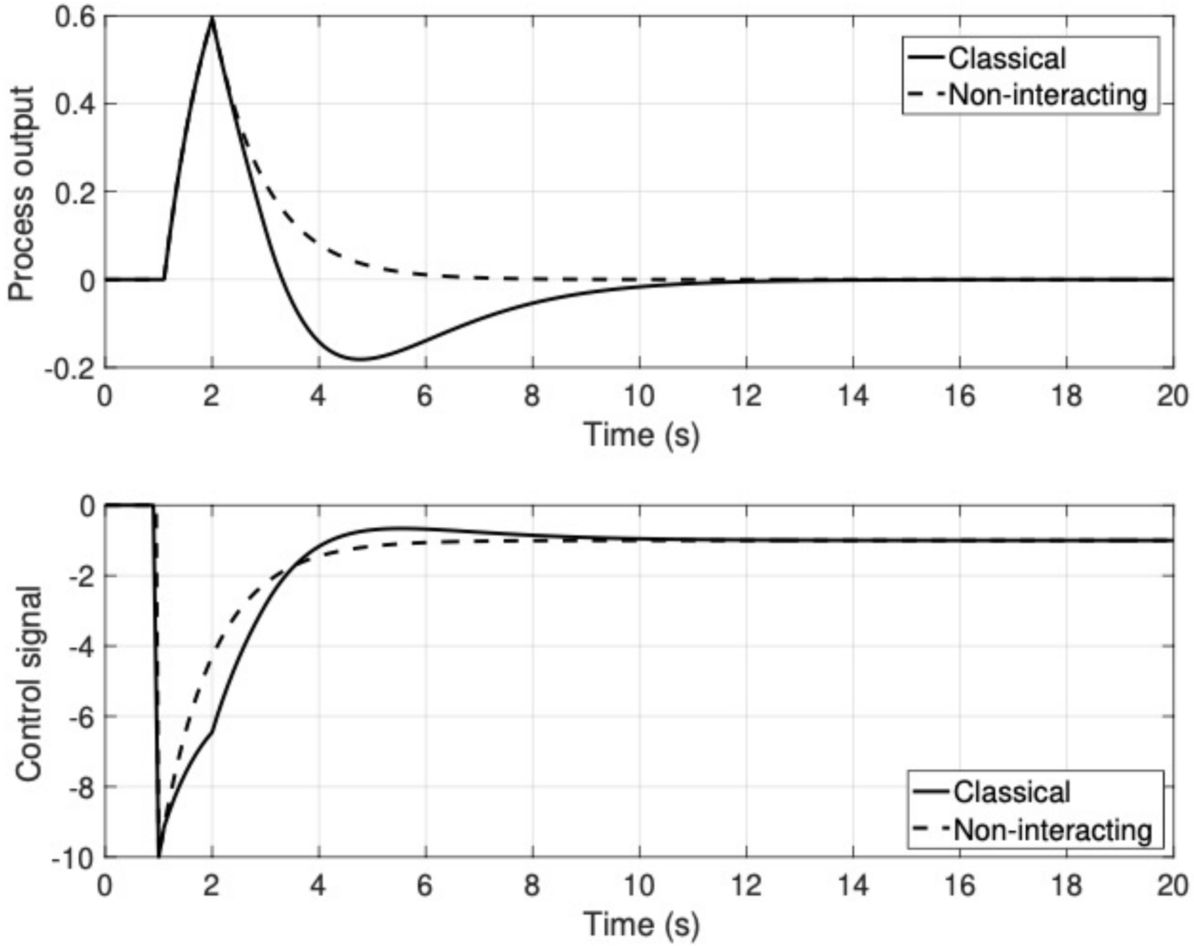
$T_d = 10$



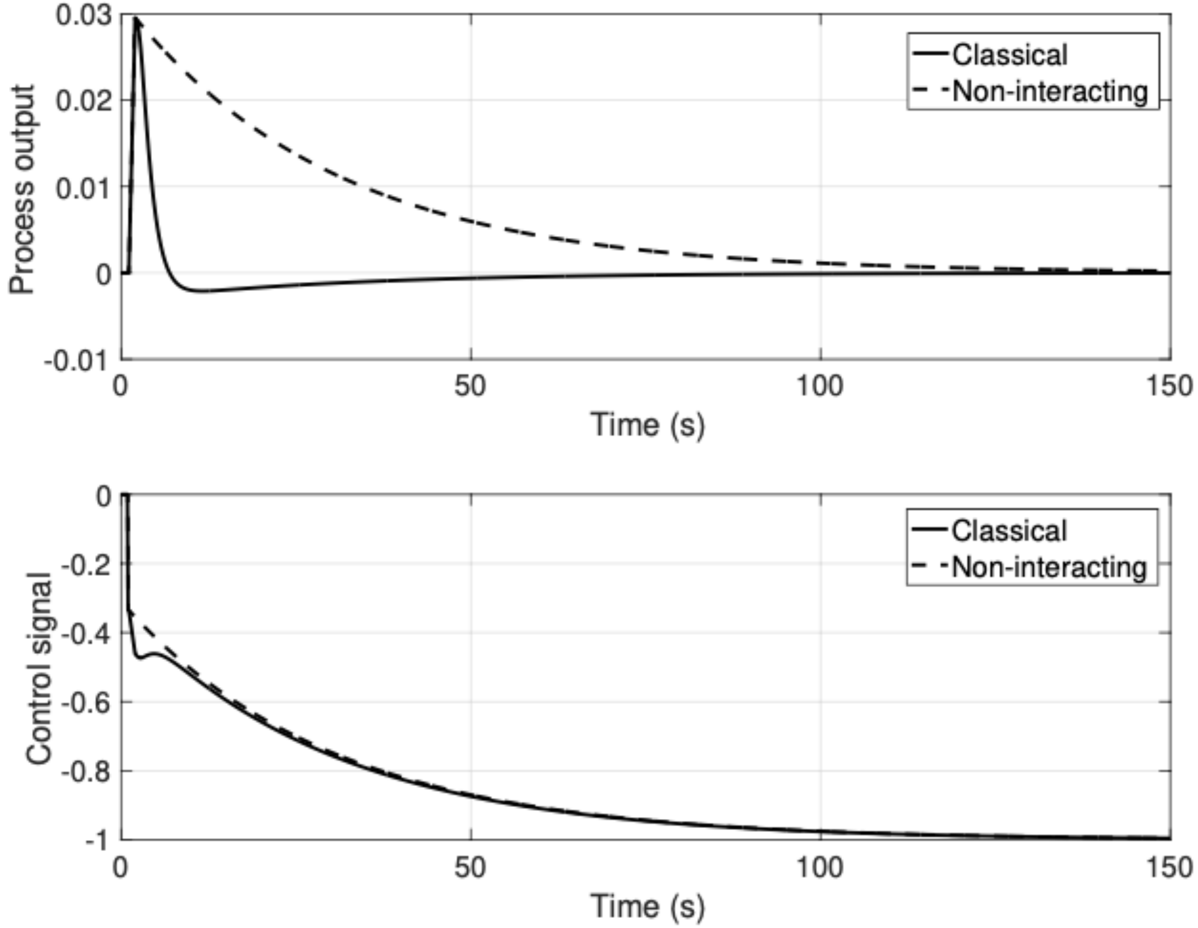
$T_d = 100$

Performance indexes

$$T_d = 1 < 2(L_u + \lambda) f(\lambda / T_d) = 1.497$$



$$T_d = 30 > 2(L_u + \lambda) f(\lambda / T_d) = 4.832$$



5 Conclusions

Conclusions

- The motivation for feedforward tuning rules was introduced.
- The two available feedforward control schemes were used.
- Simple tuning rules based on the process and feedback controllers' parameters were presented for both control schemes.
- The proposed rules were compared with optimal tuning parameters.
- The effect of feedforward compensator parameters was analyzed and combined with the selection of the feedforward control schemes.
- Performance indices for feedforward control were proposed.

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