Selecting control schemes and tuning rules in feedforward control

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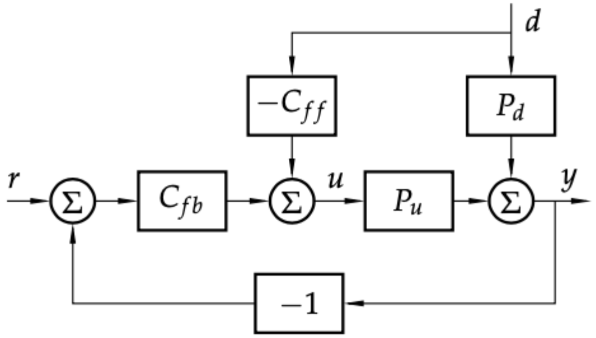
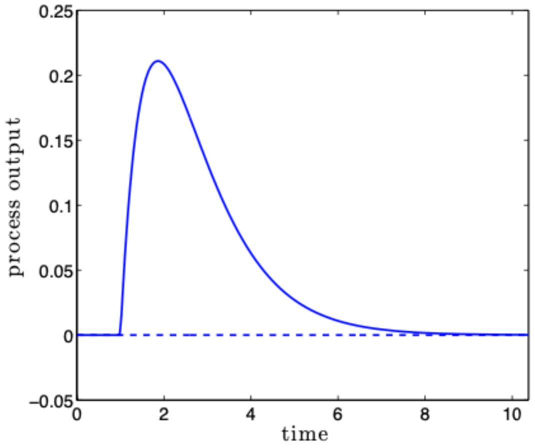
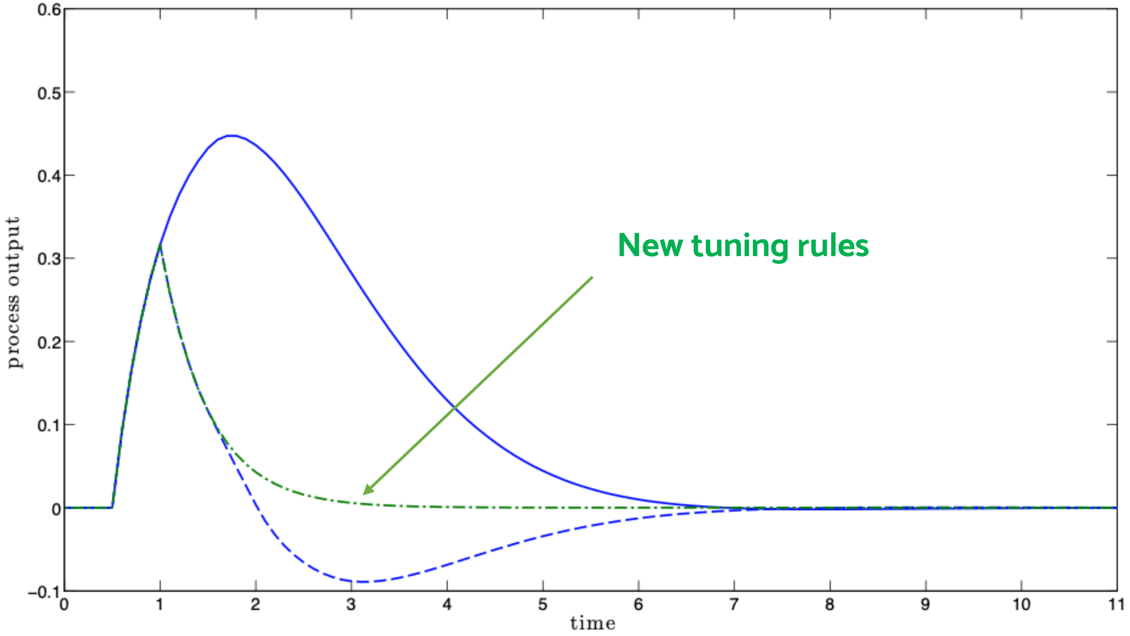
What will we see in this presentation?





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



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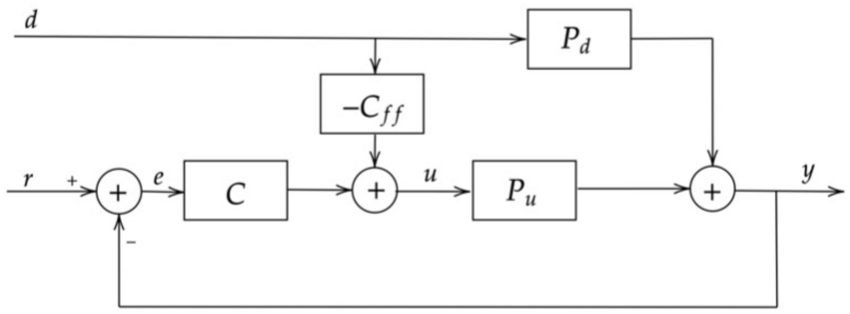

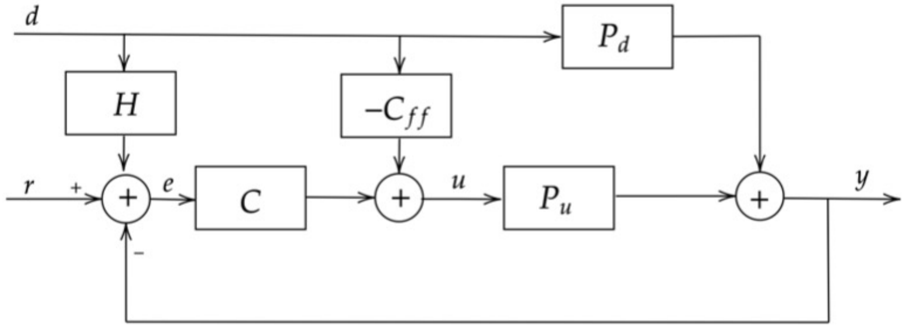

CS	Rule	M	$\mathbf{k_{ff}}$	$\mathbf{T_p}$	$\mathbf{T_z}$
C	1	OS	$(K_d/K_u)e^{(L_d-L_u)/T_d}$	T_d	T_u
C	2	OS	$\frac{K_d(T_u+\lambda)}{K_u(T_d+\lambda)})\epsilon \quad T_u \neq T_d$ $\frac{K_d}{K_u}e^{(L_d-L_u)/T_d} \quad T_u = T_d$ $\epsilon = e^{(L_u/(T_u+\lambda)-L_d/(T_d+\lambda))}$	–	–
C	3	OS	$K_d/K_u - (K/\tau_i)IE$	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

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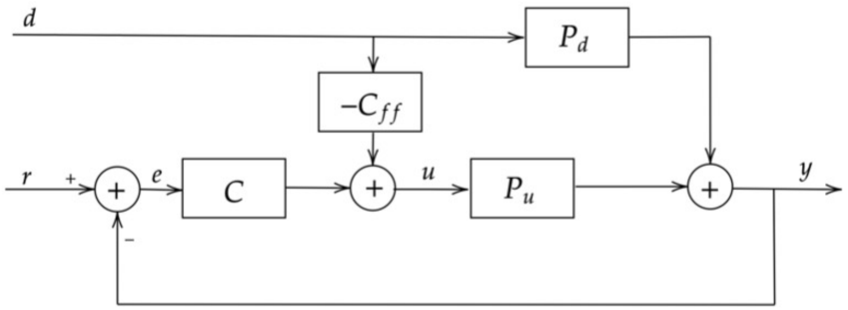
Preliminaries

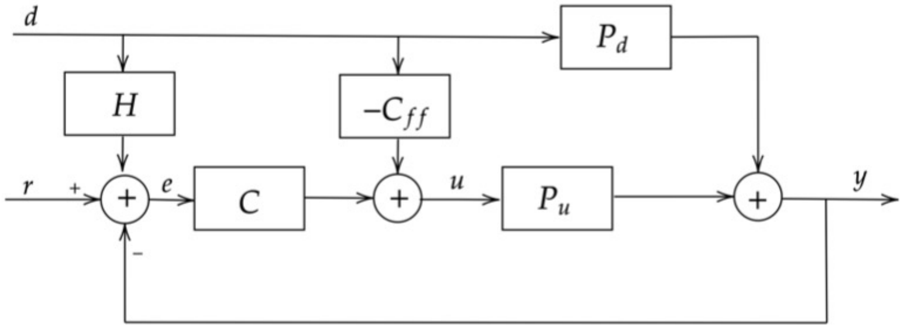
$$P_u = \frac{K_u}{1+sT_u}e^{-sL_u} \qquad P_d = \frac{K_d}{1+sT_d}e^{-sL_d}$$

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

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

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





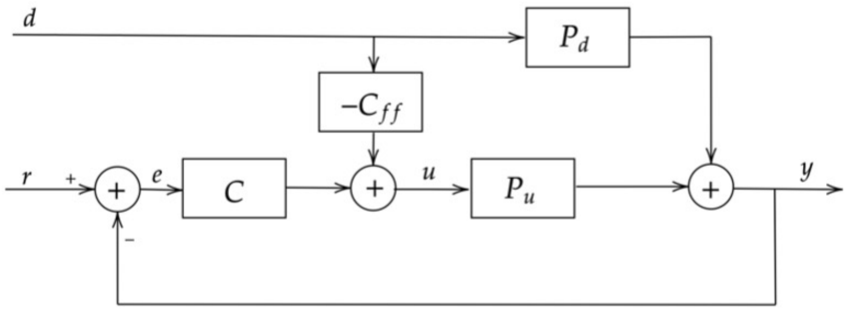
Preliminaries

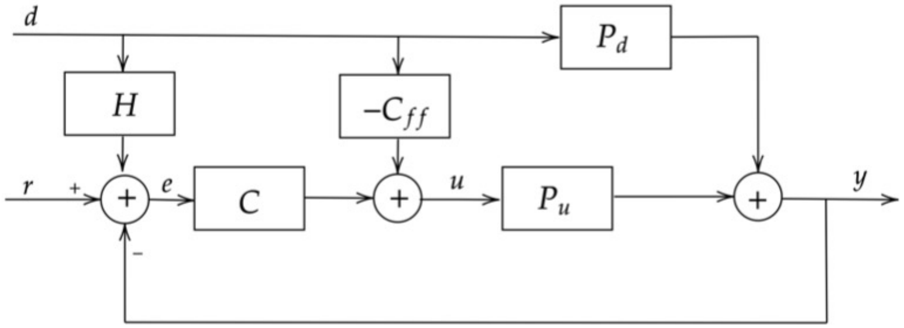
$$G_{y/d} = \frac{P_d - P_u C_{ff}}{1 + C P_u} \qquad C_{ff} = \frac{P_d}{P_u}$$

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

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

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





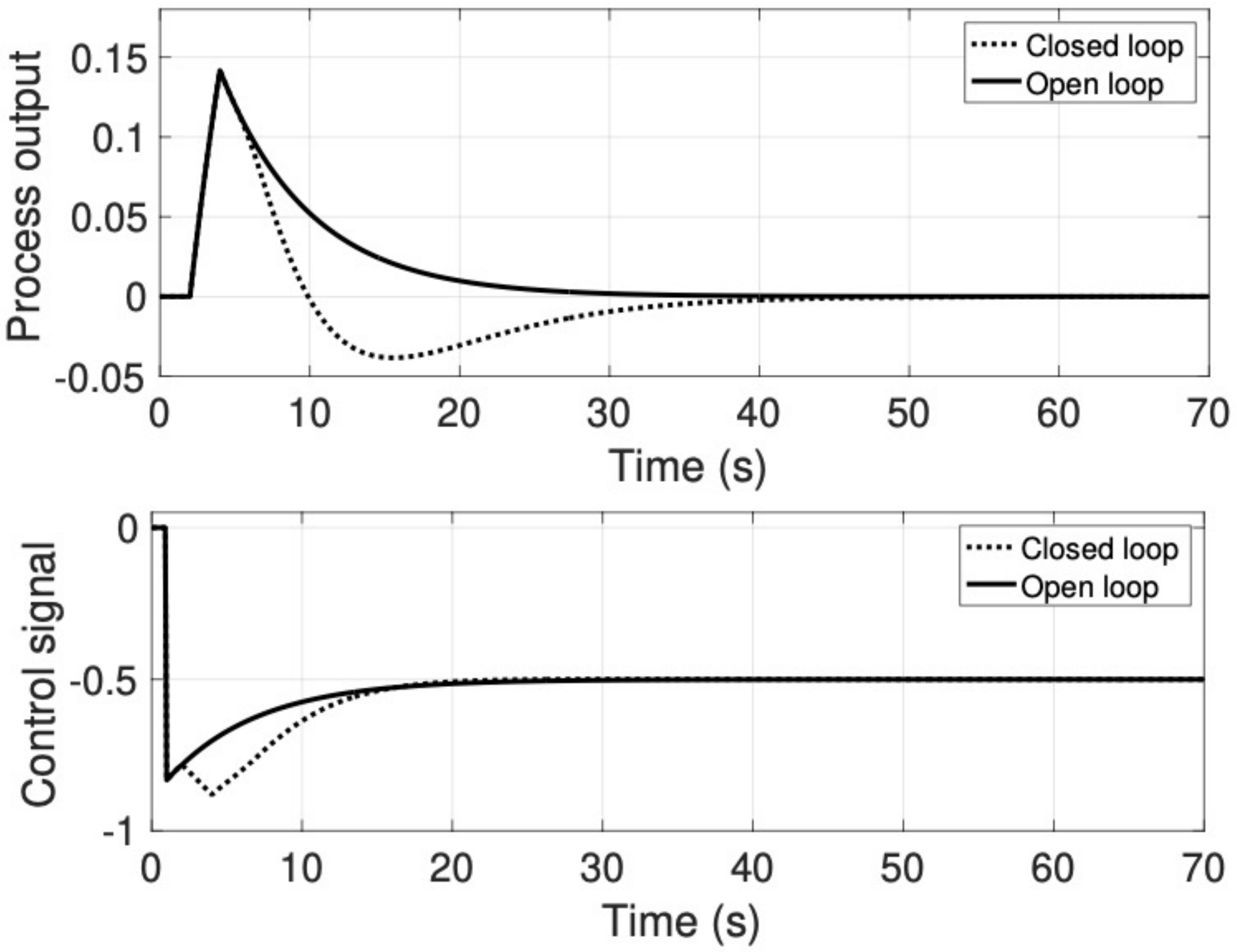
Preliminaries

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

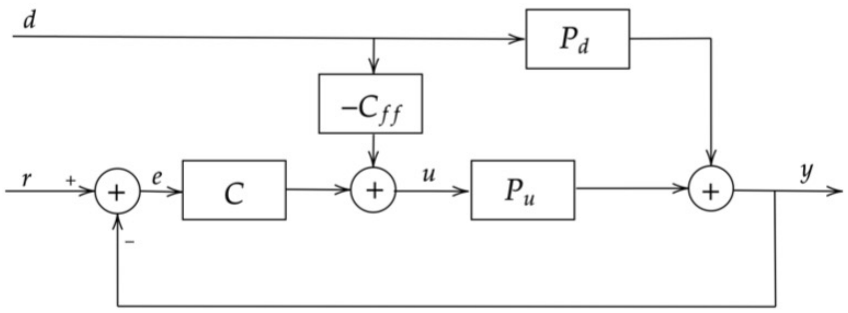
$$\tau_i = T_u = 10$$

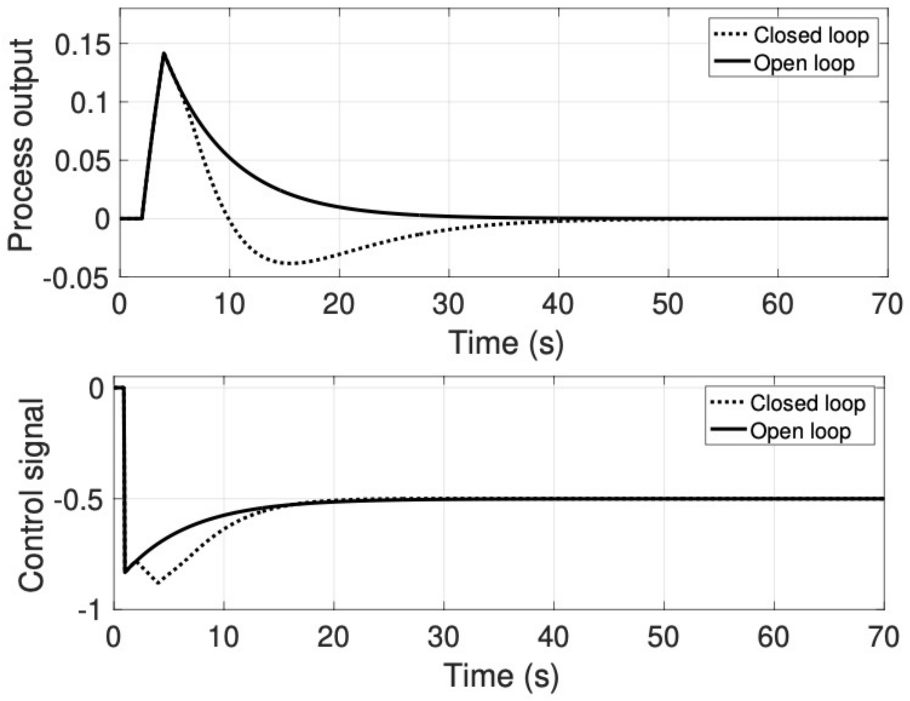
$$\lambda > (0.5+\sqrt{2})L_u$$

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



Preliminaries



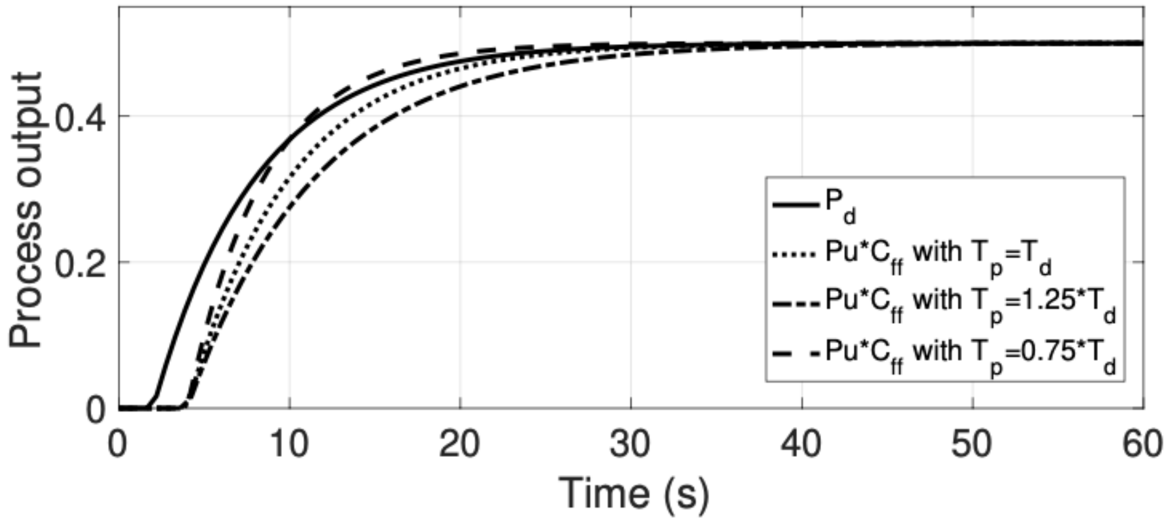


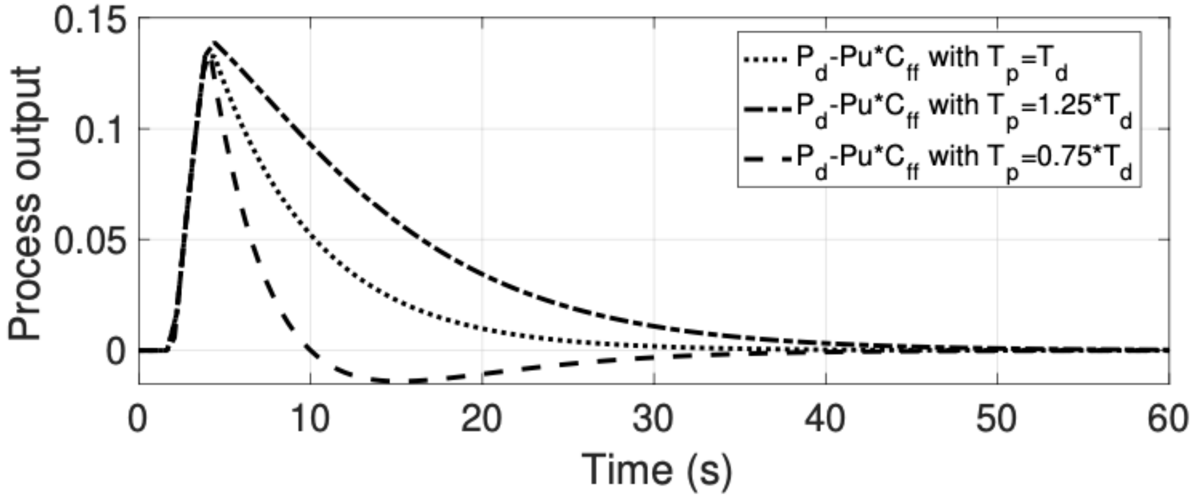
$$G_{y/d} = \frac{P_d - P_u C_{ff}}{1 + C P_u}$$

Residual term!

Feedback and feedforward interaction!

Preliminaries





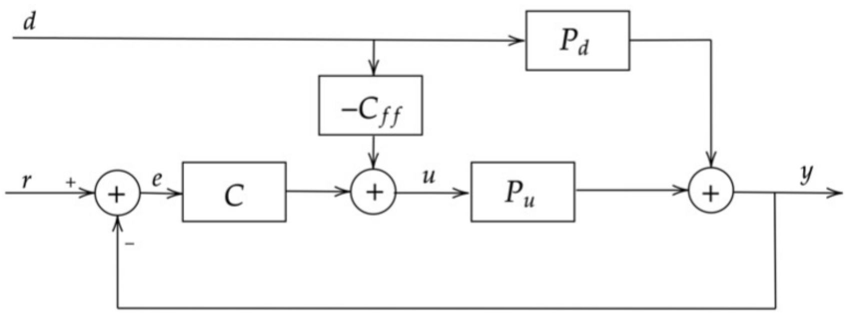
$$G_{ol} = P_d - P_u C_{ff}$$

There is room for improvment!

2 Tuning rules

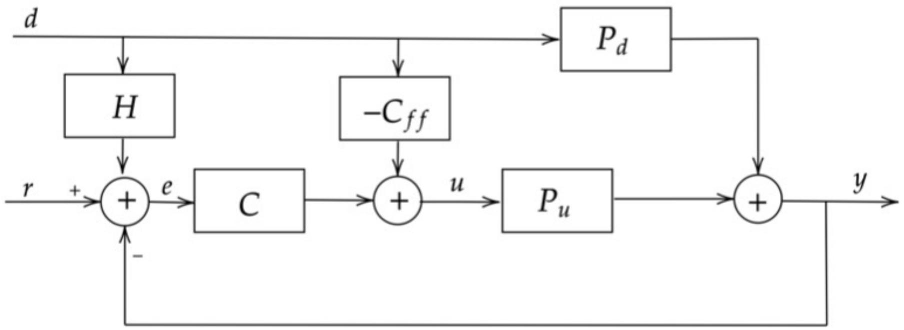
Tuning rules

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

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C	5	IAE	$(K_d\,(T_d+L_d))/(K_u\,(T_d+L_u))$	T_d	T_u
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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 $a = T_u/T_d$ $b = a(a+1)e^{L/T_d}$	$(T_p+T_u)\eta$ $\eta = \left(1-\frac{2T_u}{b(T_d+T_p)}\right)$
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$IE = K_d\,(L_u-L_d+T_u-T_d+T_p-T_z)$					

$$\textbf{Static} \quad C_{ff} = k_{ff}$$

$$\textbf{Lead}-\textbf{lag} \quad C_{ff} = k_{ff}\frac{1+sT_z}{1+sT_p}$$

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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:*

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

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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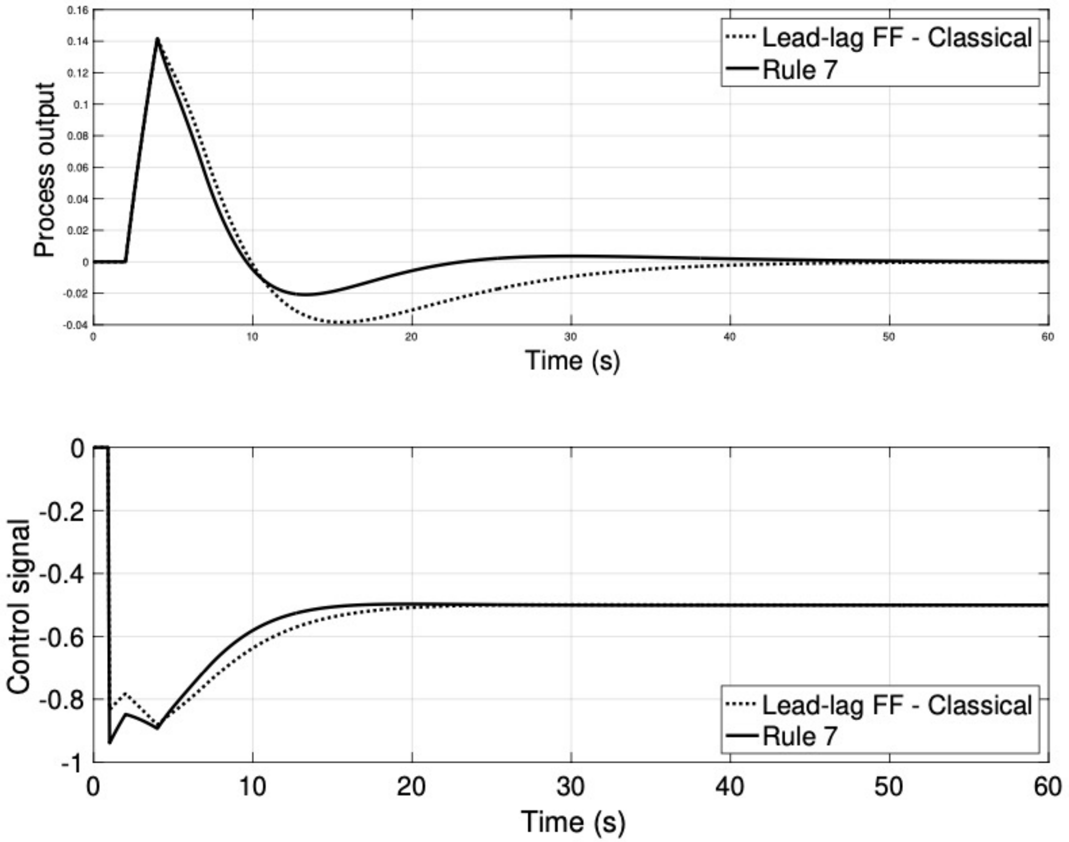
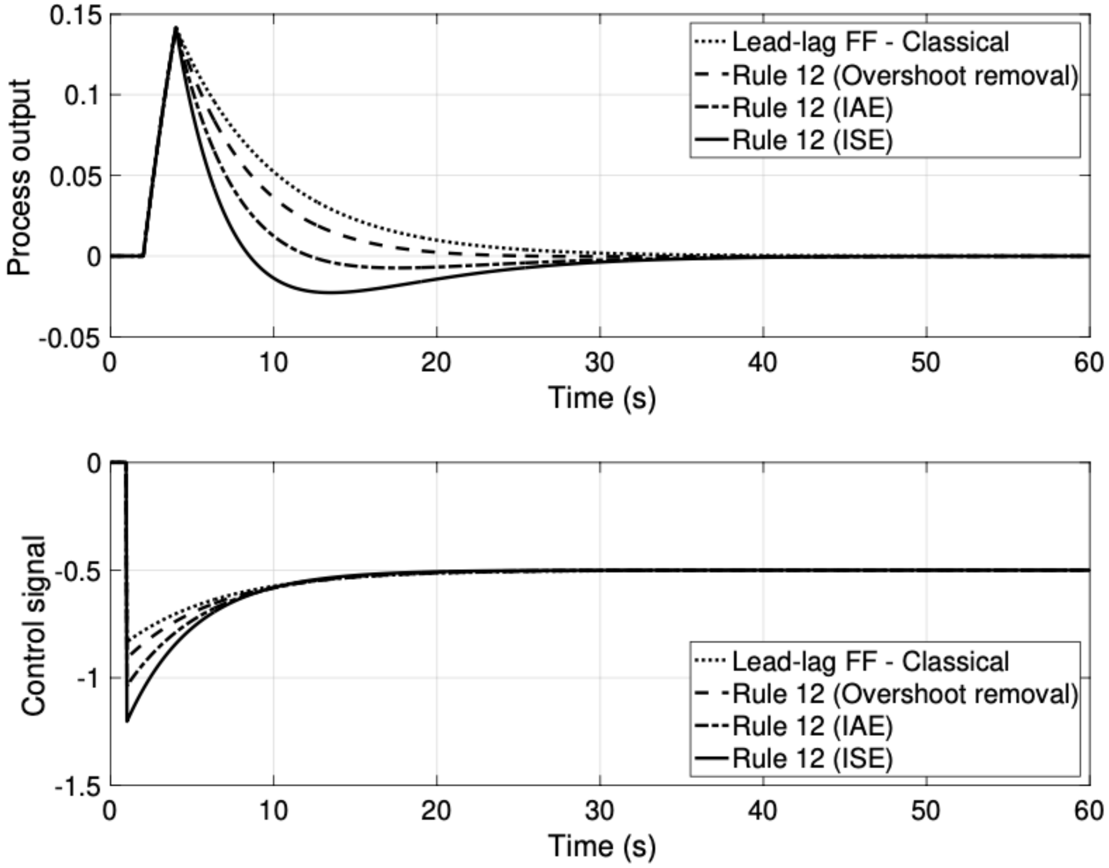
Tuning rules

Classical scheme



35% IAE reduction
45% Overshoot reduction

Non-interactive scheme

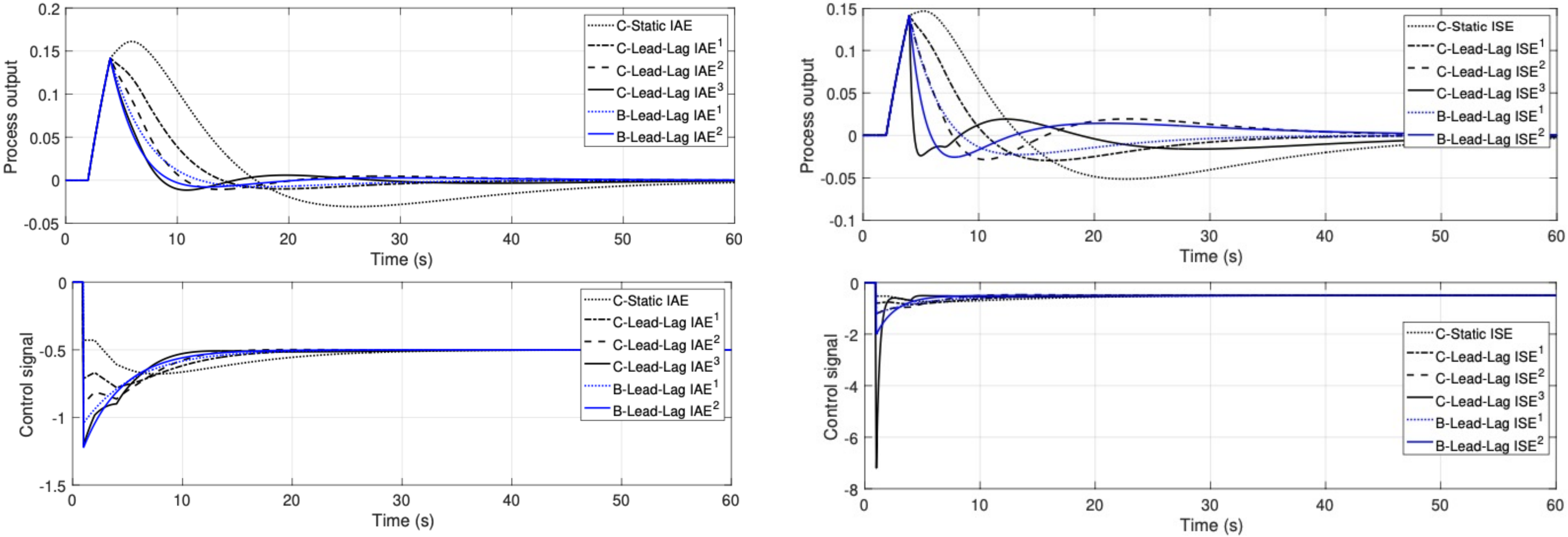


38% IAE reduction
47% ISE reduction

3 Selecting control schemes and tuning rules

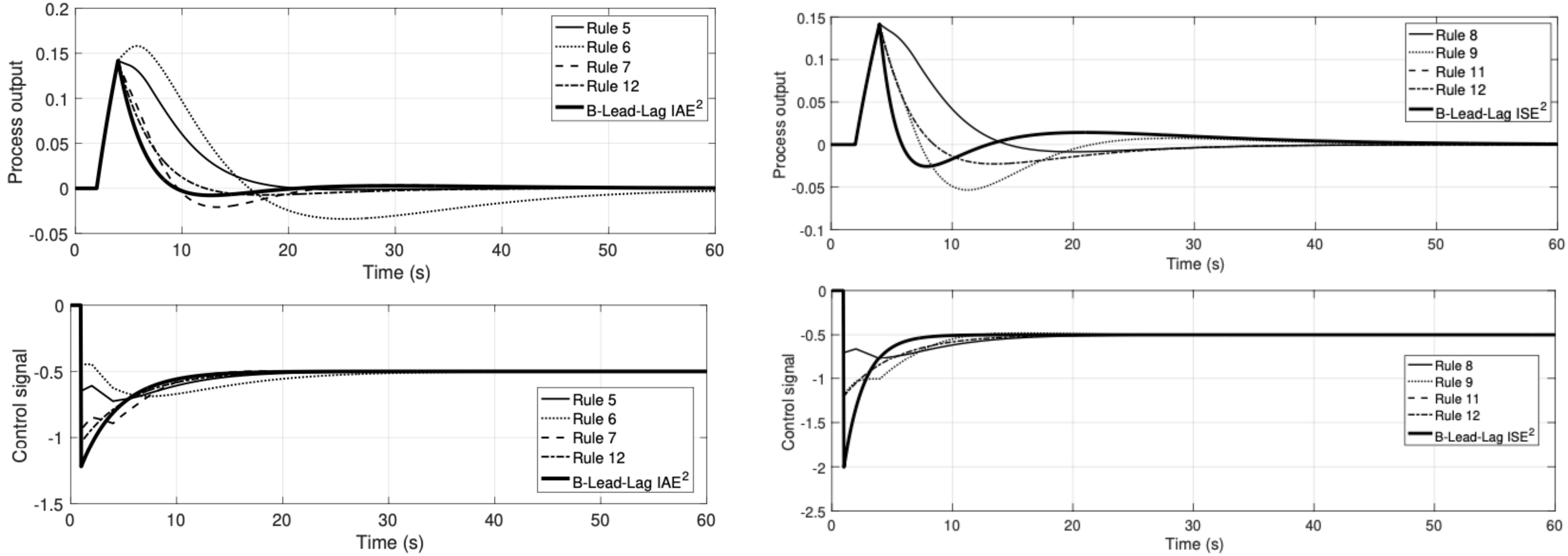
Selecting control scheme and tuning rules

Obtaining optimal tuning values



Selecting control scheme and tuning rules

Comparing the rules with the optimal rule



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Selecting control scheme and tuning rules

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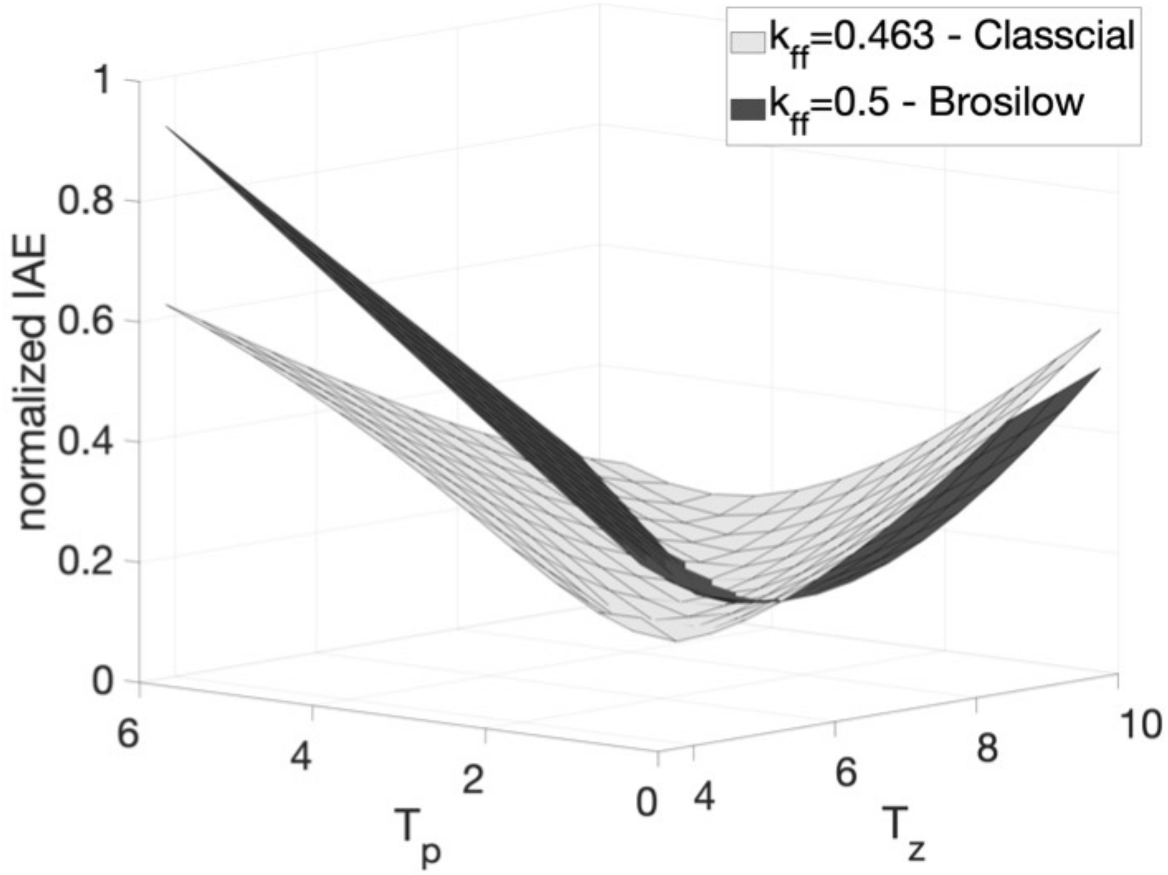
Rules	IAE_{norm}	ISE_{norm}	overshoot	peak	k_{ff}	T_z	T_p
FB	1	1	0	9.57	–	–	–
C-IAE[1]	0.212	0.091	1.99	55.68	0.427	10	6
C-IAE[2]	0.16	0.06	2.16	80.02	0.434	10	4.825
C-IAE[3]	0.131	0.044	2.33	140.65	0.463	7.36	2.834
C-ISE[1]	0.238	0.08	5.89	70.52	0.48	10	6
C-ISE[2]	0.19	0.05	5.64	141.24	0.436	10	3.611
C-ISE[3]	0.165	0.028	4.84	1339.83	0.517	3.968	0.285
B-IAE[1]	0.143	0.052	1.53	108.075	0.5	10	4.806
B-IAE[2]	0.118	0.042	1.56	143.971	0.5	8.763	3.592
B-ISE[1]	0.16	0.047	4.53	140.508	0.5	10	4.158
B-ISE[2]	0.151	0.033	5.13	301.412	0.5	6.79	1.692

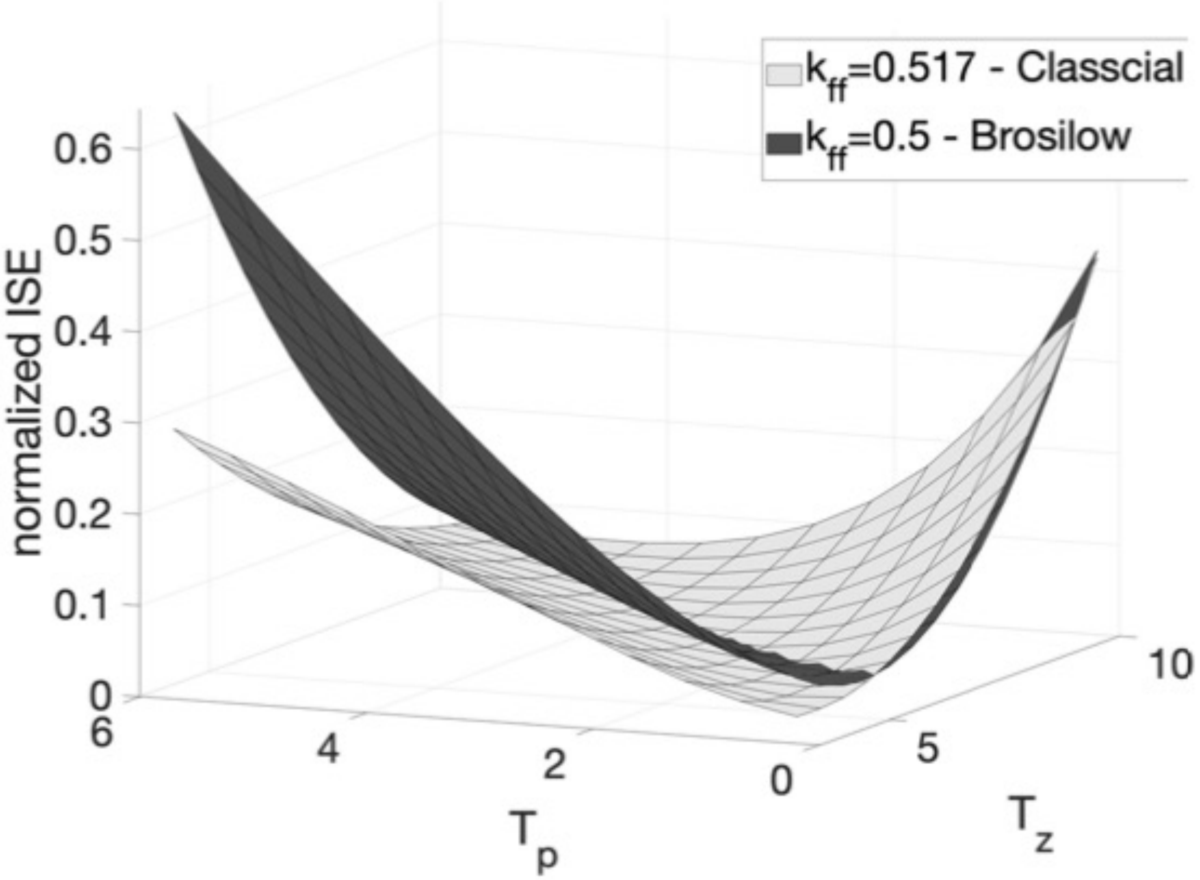
Table 1. Results of optimally tuned feedforward compensators

Rules	IAE_{norm}	ISE_{norm}	overshoot	peak	k_{ff}	T_z	T_p
FB	1	1	0	9.57	–	–	–
Lead-Lag	0.257	0.082	7.67	76.28	0.5	10	6
Rule 1 (IAE)	0.166	0.059	4.18	87.79	0.453	10	4.824
Rule 1 (ISE)	0.207	0.061	10.66	136.17	0.491	10	4.158
Rule 2	0.232	0.113	0.3	45.07	0.389	10	6
Rule 3	0.212	0.094	1.7	54.29	0.422	10	6
Lead-Lag	0.229	0.089	0	66.67	0.5	10	6
Rule 4 (IAE)	0.143	0.053	1.46	107.32	0.5	10	4.824
Rule 4 (ISE)	0.16	0.047	4.53	140.51	0.5	10	4.158
Rule 5	0.151	0.033	5.13	301.57	0.5	6.789	1.691

Table 2. Summary of the results for the tuning rules.

Selecting control scheme and tuning rules





4 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.

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4th IFAC Conference on Advances in Proportional - Integral - Derivative Control (PID2014)

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Important Dates:

Oct 15, 2023	Submission Open
Dec 15, 2023	Submission Deadline
Mar 1, 2024	Notification of Acceptance
Mar 15, 2024	Early Registration Deadline
May 1, 2024	Late Registration Deadline

Registration:
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