Advances in Feedforward Control for Measurable Disturbances

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Outline

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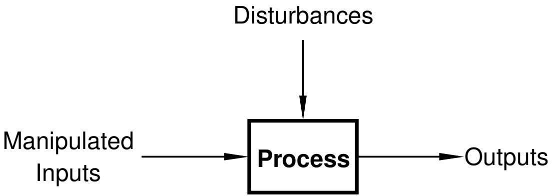
1. Introduction
2. Feedforward control problem
3. Nominal feedforward tuning rules
   - Non-realizable delay
4. Performance indices for feedforward control
5. Conclusions

What are load disturbances?

- Typically low frequency input signals which affect the output of processes but that cannot be manipulated

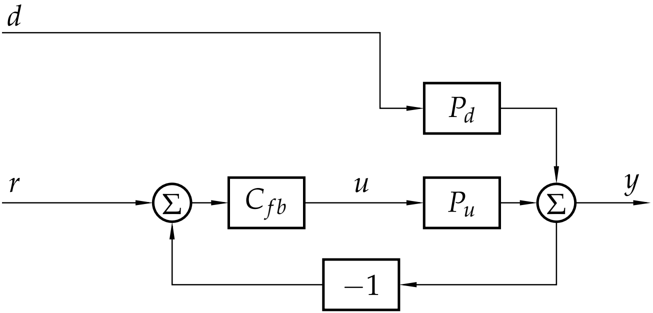


Introduction

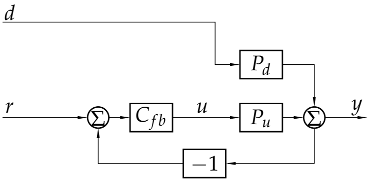
- Most industrial processes are subject to disturbances and the nature and origin of disturbances may vary depending on the process and the operational environments.
- Effective disturbance effect reduction **is a key topic in process control**. In fact, disturbances together with process uncertainty, are one of the reasons for feedback control.

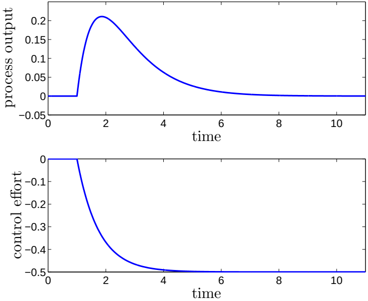
Real plants at the Automatic Control research group in Almería

Motivation: feedback controller



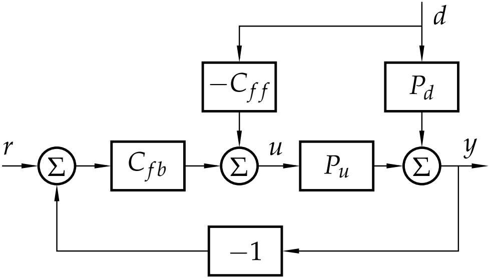
Motivation: feedback controller





No reaction until there are discrepancies!

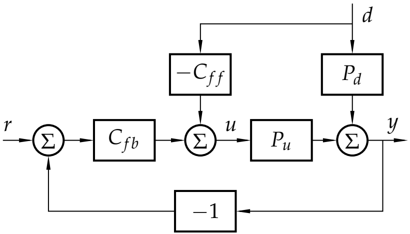
Motivation: feedforward compensator

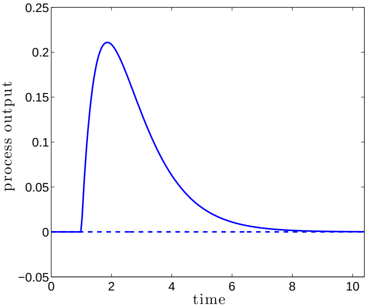


$$C_{ff} = \frac{P_d}{P_u}$$

$$Y = (P_d - P_u C_{ff})D$$

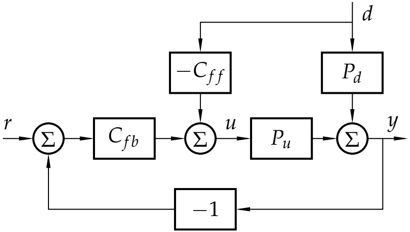
Motivation: feedforward compensator

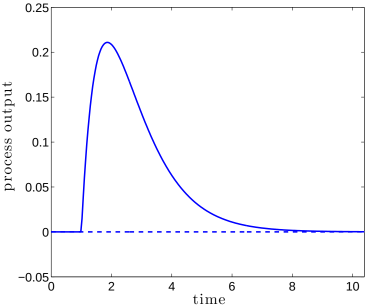




Ideal compensation: $C_{ff} = \dfrac{P_d}{P_u} = P_d \, P_u^{-1}$

Motivation: feedforward compensator





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

Feedforward control problem

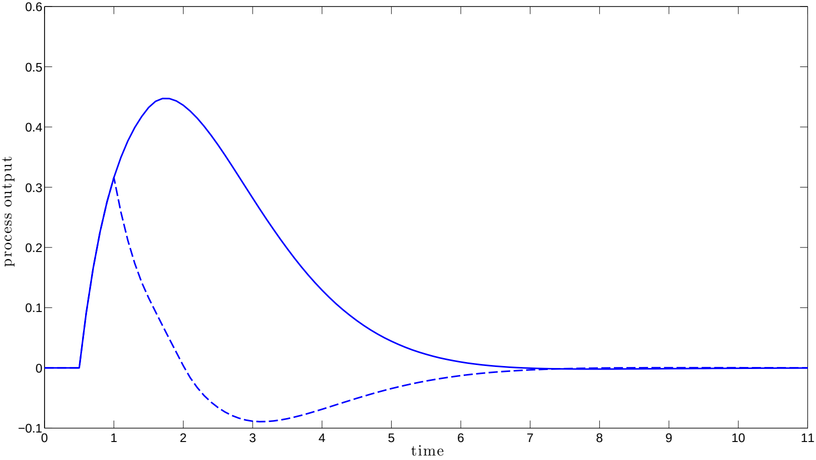
Perfect compensation is seldom realizable:

- Non-realizable delay inversion.
- Right-half plan zeros.
- Integrating poles.
- Improper transfer functions.

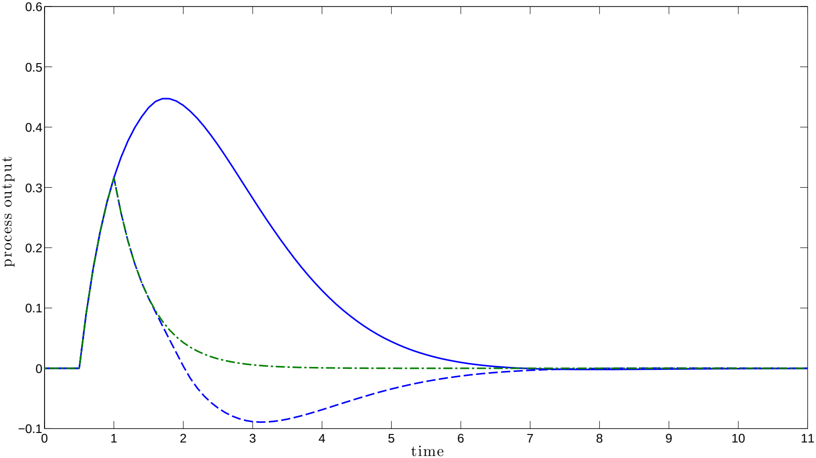
Classical solution

Ignore the non-realizable part of the compensator and implement the realizable one. In practice, static gain feedfoward compensators are quite common.

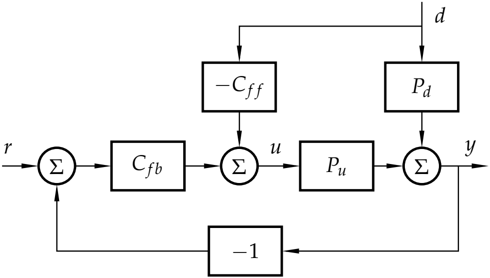
Motivation: non-ideal feedforward compensator



Motivation: non-ideal feedforward compensator



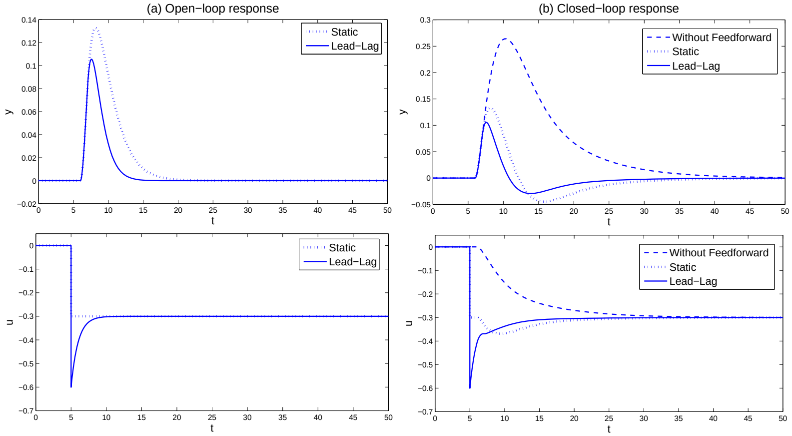
Motivation: residual term



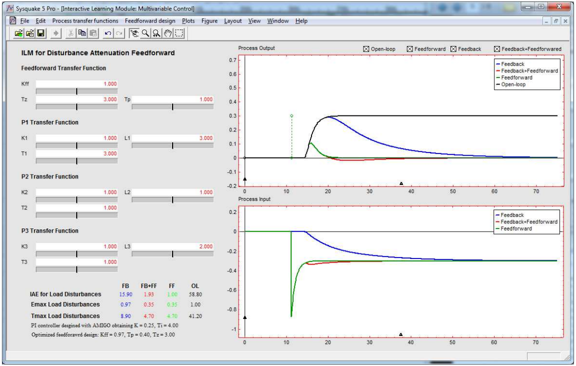
$$C_{ff} = \frac{P_d}{P_u}$$

$$Y = (P_d - P_u C_{ff})D$$

Motivation


(a) Open−loop response
Static
Lead−Lag
y
t
u
(b) Closed−loop response
Without Feedforward
Static
Lead−Lag
y
t
u

Motivation



http://aer.ual.es/ilm/ http://fichas-interactivas.pearson.es/

Motivation

An interaction between feedforward and feedback controllers arises

$$y = \frac{P_d - C_{ff}P_u}{1+L}d = \frac{P_d - C_{ff}P_u}{1+C_{fb}P_u}d$$

Other design strategies are required!

Motivation

An interaction between feedforward and feedback controllers arises

$$y = \frac{P_d - C_{ff}P_u}{1+L}d = \frac{P_d - \boxed{C_{ff}}P_u}{1+\boxed{C_{fb}}P_u}d$$

Other design strategies are required!

Introduction

Motivation

Surprisingly there are very few studies in literature (we starting the project in 2010):

- D. Seborg, T. Edgar, D. Mellichamp, Process Dynamics and Control, Wiley, New York, 1989.
- F. G. Shinskey, Process Control Systems. Application Design Adjustment, McGraw-Hill, New York, 1996.
- C. Brosilow, B. Joseph, Techniques of Model-Based Control, Prentice-Hall, New Jersey, 2002.
- A. Isaksson, M. Molander, P. Modn, T. Matsko, K. Starr, Low-Order Feedforward Design Optimizing the Closed-Loop Response, Preprints, Control Systems, 2008, Vancouver, Canada.

Objectives

1. Study and development of a control methodology to improve disturbance compensation in industrial processes
2. Definition of nominal simple optimal tuning rules for designing feedforward compensators
3. Development of a robust methodology to cope with both reference tracking and disturbance rejection, using feedforward control structures
4. Integration of the obtained nominal and robust feedforward tuning rules into a general dead-time compensation solution
5. Propose performance indices for feedforward control

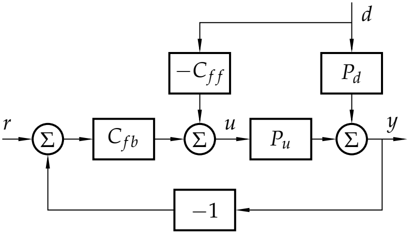
Outline

Feedforward control problem

- Feedforward control is an old topic in process control. In fact, its first application dates from 1925, where a feedforward compensator was used for drum level control of tanks connected in series.
- Many of the other early applications dealt with control of distillation columns.
- Since then, feedforward control has become a fundamental control technique for the compensation of measurable disturbances.
- *Nowadays, this mechanism is implemented in most distributed control systems to improve the control performance*.

Feedforward control problem

The idea behind feedforward control from disturbances is to supply control actions before the disturbance affects the process output:



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

Feedforward control problem

In industry, PID control is commonly used as feedback controller and four structures of the feedforward compensator are widely considered:

$$C_{fb} = \kappa_{fb}\left(1 + \frac{1}{s\tau_i} + s\tau_d\right)$$

Static:	$C_{ff} = \kappa_{ff}$
Static with delay:	$C_{ff} = \kappa_{ff}e^{-sL_{ff}}$
Lead-lag:	$C_{ff} = \kappa_{ff}\dfrac{1 + s\beta_{ff}}{1 + s\tau_{ff}}$
Lead-lag with delay:	$C_{ff} = \kappa_{ff}\dfrac{1 + s\beta_{ff}}{1 + s\tau_{ff}}e^{-sL_{ff}}$

Feedforward control problem

Then, if we consider that process transfer functions are modeled as first-order systems with time delay, i.e.

$$P_u = \frac{\kappa_u}{1+\tau_u} e^{-s\lambda_u}, \quad P_d = \frac{\kappa_d}{1+s\tau_d} e^{-s\lambda_d}$$

The following feedforward compensator can be considered:

Static: $C_{ff} = \frac{\kappa_d}{\kappa_u}$

Static with delay: $C_{ff} = \frac{\kappa_d}{\kappa_u} e^{-s(\lambda_d-\lambda_u)}$

Lead-lag: $C_{ff} = \frac{\kappa_d}{\kappa_u} \frac{1+s\tau_u}{1+s\tau_d}$

Lead-lag with delay: $C_{ff} = \frac{\kappa_d}{\kappa_u} \frac{1+s\tau_u}{1+s\tau_d} e^{-s(\lambda_d-\lambda_u)}$

Feedforward control problem

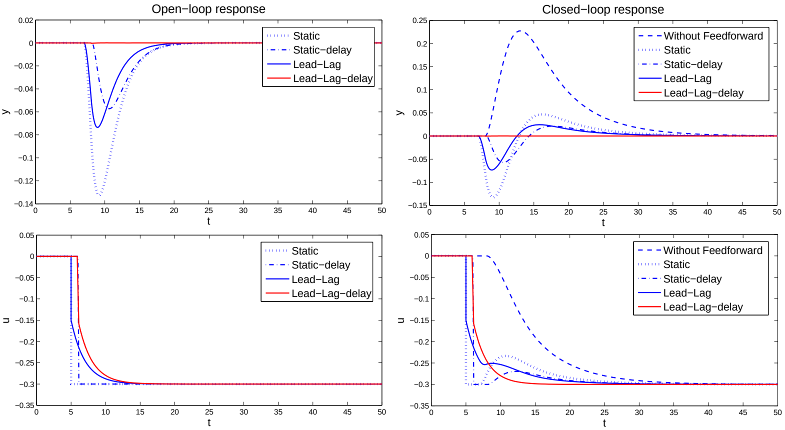
Lets consider the following example:

$$P_u(s) = \frac{1}{s+1}e^{-s}, \quad P_d(s) = \frac{1}{2s+1}e^{-2s}$$

$$\begin{array}{ll} \text{Static:} & C_{ff} = 1 \\ \text{Static with delay:} & C_{ff} = e^{-s} \\ \text{Lead-lag:} & C_{ff} = \dfrac{1+s}{1+2s} \\ \text{Lead-lag with delay:} & C_{ff} = \dfrac{1+s}{1+2s}e^{-s} \end{array}$$

C_{fb} is a PI controller tuned using the AMIGO rule, $\kappa_{fb} = 0.25$ and $\tau_i = 2.0$.

Feedforward control problem



Motivation

Then, lets consider a delay inversion problem, i.e., $\lambda_d < \lambda_u$. Then, the resulting feedforward compensators are given by:

$$C_{ff} = K_{ff} = \frac{\kappa_d}{\kappa_u}$$

$$C_{ff} = \frac{\kappa_d}{\kappa_u}\frac{\tau_u s + 1}{\tau_d s + 1}$$

Motivation

Example:

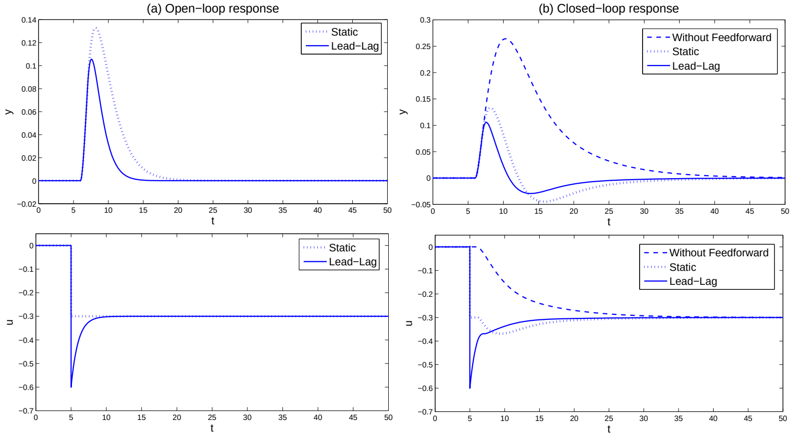
$$P_u(s) = \frac{1}{2s+1}e^{-2s}, \quad P_d(s) = \frac{1}{s+1}e^{-s}$$

$$C_{ff} = 1, \quad C_{ff} = \frac{2s+1}{s+1}$$

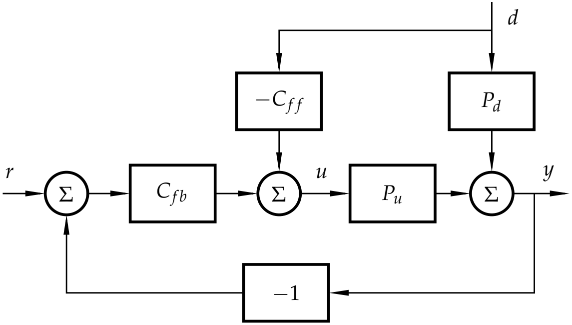
The feedback controller is tuned using the AMIGO rule, which gives the parameters $\kappa_{fb} = 0.32$ and $\tau_i = 2.85$.

Feedforward control problem

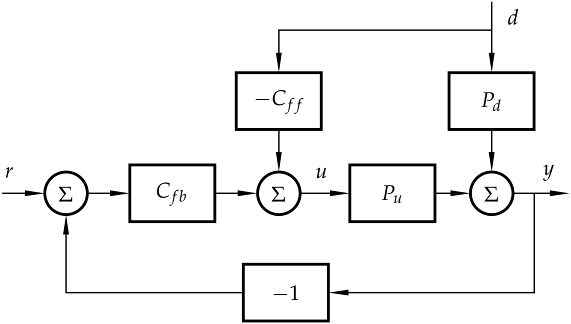
Motivation



Feedforward control problem



$$y = \frac{P_d - C_{ff}P_u}{1+L}d = \frac{P_d - C_{ff}P_u}{1+C_{fb}P_u}d$$



$$e = \frac{r}{1 + P_u C_{fb}}, \qquad e = \frac{r + P_d^*(e^{-\lambda_u s} - e^{-\lambda_d s})d}{1 + P_u C_{fb}},\ P_d = P_d^* e^{-\lambda_d}$$

Outline

Feedforward tuning rules

Cases to be evaluated in this research:

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

Outline

Nominal feedforward design: non-realizable delay

Objective

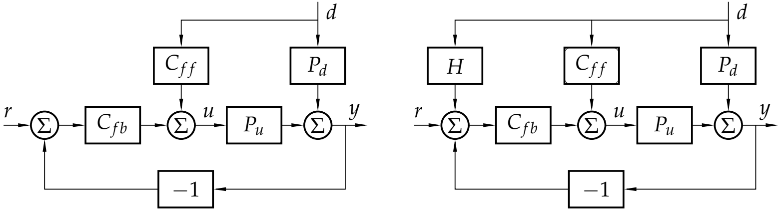
To improve the final disturbance response of the closed-loop system when delay inversion is not realizable ($\lambda_u > \lambda_d$)

Methodology

- Adapt the open-loop tuning rules to closed-loop design
- Obtain optimal open-loop tuning rules
- Design a switching controller to improve the results

Nominal feedforward design: non-realizable delay

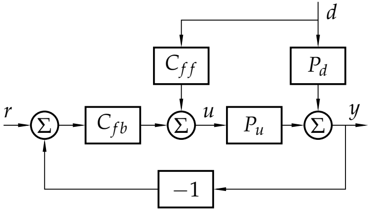
Two approaches:



$$P_k(s) = \frac{\kappa_k}{\tau_k s + 1} e^{-\lambda_k s} \qquad k \in [u, d] \qquad \lambda_u > \lambda_d$$

$$C_{fb}(s) = \kappa_{fb} \frac{\tau_i s + 1}{\tau_i s} \qquad C_{ff}(s) = \kappa_{ff} \frac{\beta_{ff} s + 1}{\tau_{ff} s + 1}$$

Two approaches:



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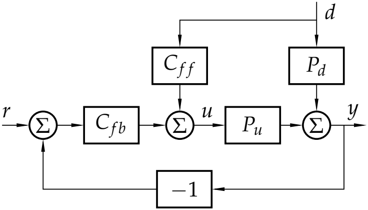
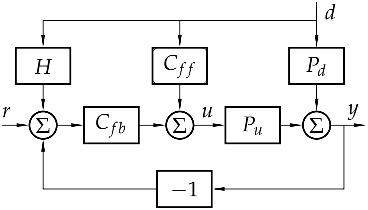
Nominal feedforward design: non-realizable delay

Two approaches:





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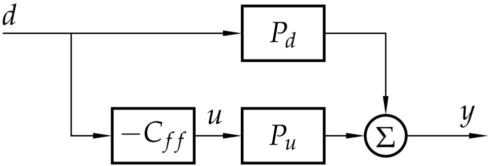
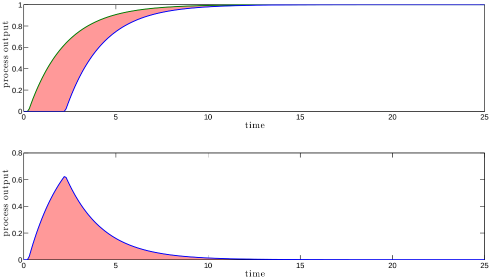
Nominal feedforward design: non-realizable delay

Delay inversion: open-loop compensation



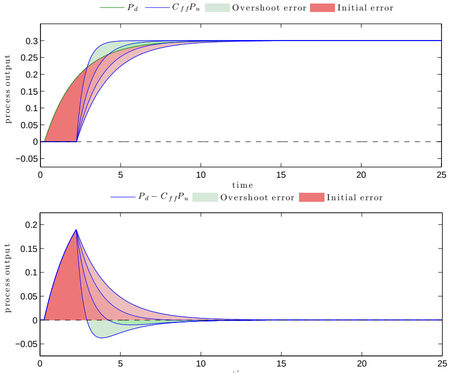
$$y = P_{ff} = \left(P_d - C_{ff} P_u\right) d \qquad C_{ff} = \frac{\kappa_d}{\kappa_u} \cdot \frac{\tau_u s + 1}{\tau_d s + 1}$$

Delay inversion: open-loop compensation



$$y = P_{ff} = \left(P_d - C_{ff}P_u\right)d \qquad C_{ff} = \frac{\kappa_d}{\kappa_u}\cdot\frac{\tau_u s+1}{\tau_d s+1}$$

Delay inversion: open-loop compensation



$$y = P_{ff} = \left(P_d - C_{ff}P_u\right) d + u_{fb}P_u$$

Nominal feedforward design: non-realizable delay

First approach

To deal with the non-realizable delay case, the first approach was to work with the following:

- Use the classical feedforward control scheme.
- Remove the overshoot observed in the response.
- Proposed a tuning rule to minimize Integral Absolute Error (IAE).
- The rules should be simple and based on the feedback and model parameters.

Nominal feedforward design: non-realizable delay

To remove the overshoot, the feedback control action is taken into account to calculate the feedforward gain, κ_{ff}.

$$\Delta u = \frac{\kappa_{fb}}{\tau_i} \int e dt = \frac{\kappa_{fb}}{\tau_i} IE \cdot d$$

So, in the new rule, the goal is to take the control signal to the correct stationary level $-\Delta u$ in order to take the feedback control signal into account and reduce the overshoot. The gain is therefore reduced to

$$\kappa_{ff} = \frac{k_d}{k_u} - \frac{\kappa_{fb}}{\tau_i} IE$$

Closed-loop design

Nominal feedforward design: non-realizable delay

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Closed-loop design

Nominal feedforward design: non-realizable delay

IE estimation:

$$Y = (P_d - P_u C_{ff})D = P_d D - P_u C_{ff} D$$

$$y(t) - y_{sp} = \begin{cases} k_d \left(1 - e^{-\frac{t}{\tau_d}}\right) d & 0 \leq t \leq \lambda_b \\ k_d \left(\left(1 - e^{-\frac{t}{\tau_d}}\right) - \left(1 - e^{-\frac{t-\lambda_b}{T_b}}\right)\right) d & \lambda_b < t \end{cases}$$

$$\lambda_b = \max(0, \lambda_u - \lambda_d), \quad T_b = \tau_u + \tau_{ff} - \beta_{ff}$$

Nominal feedforward design: non-realizable delay

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$$\lambda_b = \max(0, \lambda_u - \lambda_d), \quad T_b = \tau_u + \tau_{ff} - \beta_{ff}$$

Nominal feedforward design: non-realizable delay

IE estimation:

$$
\begin{aligned}
IE \cdot d &= \int_0^{\infty} (y(t) - y_{sp}) dt \\
&= k_d \int_0^{\lambda_b} \left(1 - e^{-\frac{t}{\tau_d}}\right) d\, dt + k_d \int_{\lambda_b}^{\infty} \left(-e^{-\frac{t}{\tau_d}} + e^{-\frac{t-\lambda_b}{T_b}}\right) d\, dt \\
&= k_d \left[t + \tau_d e^{-\frac{t}{\tau_d}}\right]_0^{\lambda_b} d + k_d \left[\tau_d e^{-\frac{t}{\tau_d}} - T_b e^{-\frac{t-\lambda_b}{T_b}}\right]_{\lambda_b}^{\infty} d \\
&= k_d \left(\lambda_b + \tau_d e^{-\frac{\lambda_b}{\tau_d}} - \tau_d - \tau_d e^{-\frac{\lambda_b}{\tau_d}} + T_b\right) d \\
&= k_d \left(\lambda_b - \tau_d + T_b\right) d
\end{aligned}
$$

IE estimation:

$$IE = \begin{cases} k_d(\tau_u - \tau_d + \tau_{ff} - \beta_{ff}) & \lambda_d \geq \lambda_u \\ k_d(\lambda_u - \lambda_d + \tau_u - \tau_d + \tau_{ff} - \beta_{ff}) & \lambda_d < \lambda_u \end{cases}$$

$$\kappa_{ff} = \frac{k_d}{k_u} - \frac{\kappa_{fb}}{\tau_i} IE$$

Nominal feedforward design: non-realizable delay

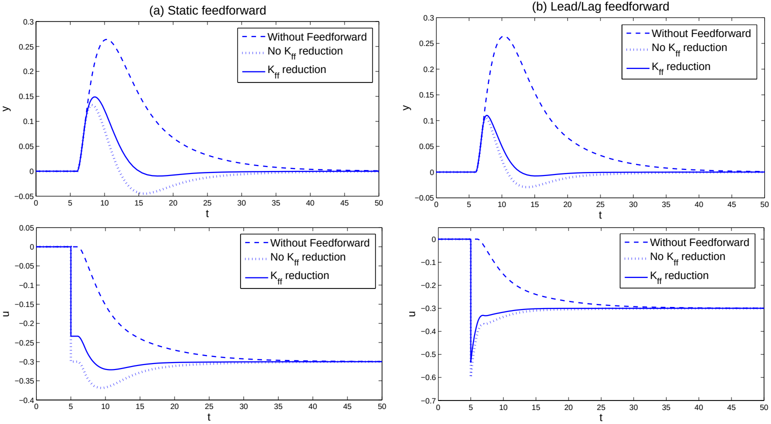
Lets consider the same previous example:

$$P_u(s) = \frac{1}{2s+1}e^{-2s}, \quad P_d(s) = \frac{1}{s+1}e^{-s}$$

$$C_{ff} = 1, \quad C_{ff} = \frac{2s+1}{s+1}$$

The feedback controller is tuned using the AMIGO rule, which gives the parameters $\kappa_{fb} = 0.32$ and $\tau_i = 2.85$.

Nominal feedforward design: non-realizable delay



The feedforward gain κ_{ff} has been reduced from 1 to 0.778 for the static feedforward and from 1 to 0.889 for the lead-lag filter.

Once the overshoot is reduced, the second goal is to design β_{ff} and τ_{ff} to minimize the IAE value. In this way, we keep $\beta_{ff} = \tau_u$ to cancel the pole of P_u and fix the pole of the compensator:

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

where t_0 is the time when y crosses the setpoint, with $y_{sp} = 0$ and $d = 1$.

Nominal feedforward design: non-realizable delay

$$y(t) - y_{sp} = \begin{cases} k_d \left(1 - e^{-\frac{t}{\tau_d}}\right) d & 0 \leq t \leq \lambda_b \\ k_d \left(\left(1 - e^{-\frac{t}{\tau_d}}\right) - \left(1 - e^{-\frac{t-\lambda_b}{T_b}}\right)\right) d & \lambda_b < t \end{cases}$$

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

$$\frac{t_0}{\tau_d} = \frac{t_0 - \lambda_b}{T_b} \rightarrow t_0 = \frac{\tau_d \lambda_b}{\tau_d - T_b} = \frac{\tau_d}{\tau_u - \tau_{ff}} \lambda_b$$

$$T_b = \tau_u + \tau_{ff} - \beta_{ff}$$

Nominal feedforward design: non-realizable delay

$$
\begin{aligned}
IAE &= \int_0^{\lambda_b} \left(1 - e^{-\frac{t}{\tau_d}}\right) dt + \int_{\lambda_b}^{t_0} \left(-e^{-\frac{t}{\tau_d}} + e^{-\frac{t-\lambda_b}{T_b}}\right) dt - \int_{t_0}^{\infty} \left(-e^{-\frac{t}{\tau_d}} + e^{-\frac{t-\lambda_b}{T_b}}\right) dt \\
&= \left[t + \tau_d e^{-\frac{t}{\tau_d}}\right]_0^{\lambda_b} + \left[\tau_d e^{-\frac{t}{\tau_d}} - T_b e^{-\frac{t-\lambda_b}{T_b}}\right]_{\lambda_b}^{t_0} - \left[\tau_d e^{-\frac{t}{\tau_d}} - T_b e^{-\frac{t-\lambda_b}{T_b}}\right]_{t_0}^{\infty} \\
&= \lambda_b - \tau_d + T_b + 2\tau_d e^{-\frac{t_0}{\tau_d}} - 2T_b e^{-\frac{t_0-\lambda_b}{T_b}} \\
&= \lambda_b - \tau_d + T_b + 2\tau_d e^{-\frac{\lambda_b}{\tau_d - T_b}} - 2T_b e^{-\frac{\lambda_b}{\tau_d - T_b}} \\
&= \lambda_b - \tau \left(1 - 2e^{-\frac{\lambda_b}{\tau}}\right)
\end{aligned}
$$

with $\tau = \tau_d - \tau_{ff}$.

$$\frac{d}{d\tau} IAE = -1 + 2e^{-\frac{\lambda_b}{\tau}} + 2\frac{\lambda_b}{\tau} e^{-\frac{\lambda_b}{\tau}} = -1 + 2(1+x)e^{-x} = 0$$

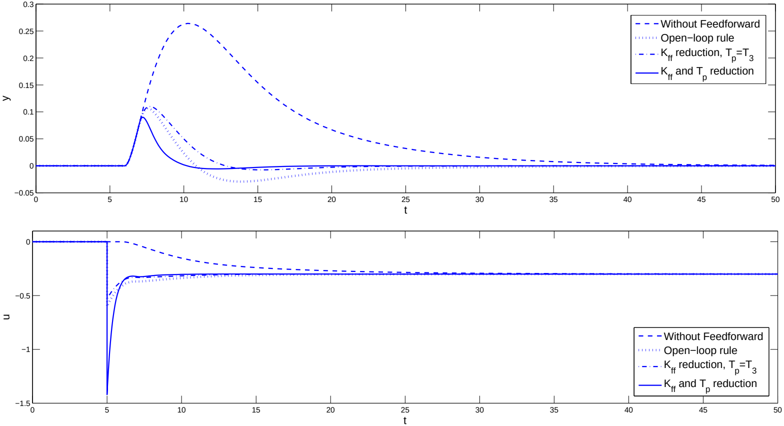
where $x = \lambda_b/\tau$. A numerical solution of this equation gives $x \approx 1.7$, which gives

$$\tau_{ff} = T_b - \tau_d + \tau_u = \tau_d - \tau \approx \tau_d - \frac{\lambda_b}{1.7}$$

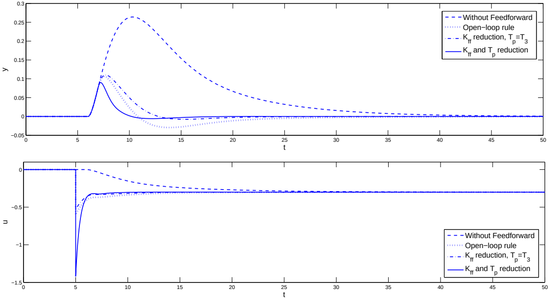
$$\tau_{ff} = \begin{cases} \tau_d & \lambda_u - \lambda_d \leq 0 \\ \tau_d - \dfrac{\lambda_u - \lambda_d}{1.7} & 0 < \lambda_u - \lambda_d < 1.7\tau_d \\ 0 & \lambda_u - \lambda_d > 1.7\tau_d \end{cases}$$

Nominal feedforward design: non-realizable delay

Gain and τ_{ff} reduction rule:



Gain and τ_{ff} reduction rule:



	No FF	Open-loop rule	κ_{ff} reduction	κ_{ff} &τ_{ff} reduction
IAE	9.03	1.76	1.37	0.59

First approach: Guideline summary

1. Set $\beta_{ff} = \tau_u$ and calculate τ_{ff} as:

$$\tau_{ff} = \begin{cases} \tau_d & \lambda_u - \lambda_d \leq 0 \\ \tau_d - \dfrac{\lambda_u - \lambda_d}{1.7} & 0 < \lambda_u - \lambda_d < 1.7\tau_d \\ 0 & \lambda_u - \lambda_d > 1.7\tau_d \end{cases}$$

2. Calculate the compensator gain, κ_{ff}, as

$$\kappa_{ff} = \frac{k_d}{k_u} - \frac{\kappa_{fb}}{\tau_i} IE$$

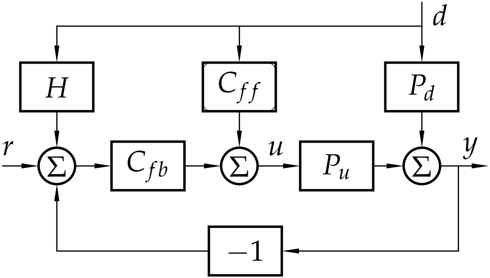
$$IE = \begin{cases} k_d(\tau_{ff} - \tau_d) & \lambda_d \geq \lambda_u \\ k_d(\lambda_u - \lambda_d - \tau_d + \tau_{ff}) & \lambda_d < \lambda_u \end{cases}$$

Second approach

To deal with the non-realizable delay case, the second approach was to work with the following:

- Use the non-interacting feedforward control scheme (feedback effect removed).
- Obtain a generalized tuning rule for τ_{ff} for moderate, aggressive and conservative responses.
- The rules should be simple and based on the feedback and model parameters.

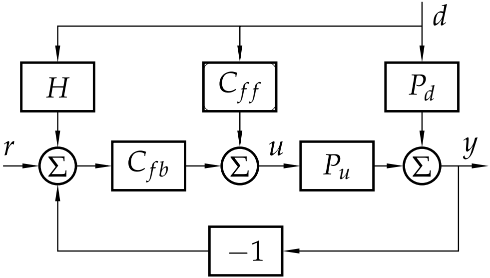
Second approach: non-interacting structure



$$y = \frac{P_{ff} + LH}{1+L} d = \left(P_{ff}\epsilon + H\eta\right) d \qquad H = P_{ff} = P_d - C_{ff}P_u$$

C. Brosilow and B. Joseph. Techniques of model-based control. Prentice Hall, New Jersey, 2012.

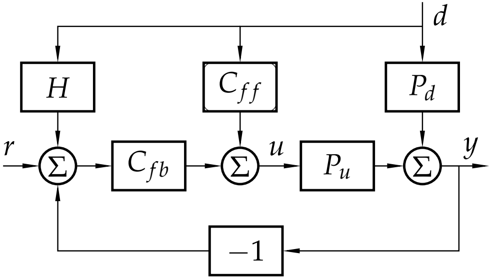
Second approach: non-interacting structure



$$y = \frac{P_{ff} + LH}{1 + L} d = \left(P_{ff}\epsilon + H\eta\right) d \qquad H = P_{ff} = P_d - C_{ff}P_u$$

C. Brosilow and B. Joseph. Techniques of model-based control. Prentice Hall, New Jersey, 2012.

Second approach: non-interacting structure



$$e = \frac{r + (H - P_d + P_u C_{ff})d}{1 + P_u C_{fb}}, \quad H = P_{ff} = P_d - P_u C_{ff}$$

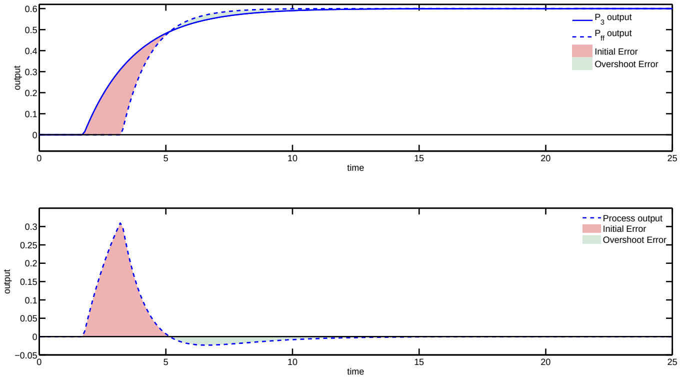
Second approach

The main idea of this second approach relies on analyzing the residual term appearing when perfect cancelation is not possible:

$$\frac{y}{d} = P_d - P_u C_{ff} = P_d - P_{ff}, \quad P_{ff} = P_u C_{ff}$$

$$\frac{y}{d} = \frac{k_d}{\tau_d s + 1} e^{-\lambda_d s} - \frac{k_d}{\tau_{ff} s + 1} e^{-\lambda_u s}$$

Nominal feedforward design: non-realizable delay



$$\frac{y}{d} = \frac{k_d}{\tau_d s + 1} e^{-\lambda_d s} - \frac{k_d}{\tau_{ff} s + 1} e^{-\lambda_u s}$$

Nominal feedforward design: non-realizable delay

From the previous analysis, it can be concluded that in order to totally remove the overshoot for the disturbance rejection problem by using a lead-lag filter, the settling times of both transfer functions must be the same:

$$\frac{y}{d} = \frac{k_d}{\tau_d s + 1} e^{-\lambda_d s} - \frac{k_d}{\tau_{ff} s + 1} e^{-\lambda_u s}$$

$$\tau_{ff} = \frac{4\tau_d + \lambda_d - \lambda_u}{4} = \tau_d - \frac{\lambda_b}{4}, \quad \lambda_b = \lambda_d - \lambda_u$$

From the previous analysis, it can be concluded that in order to totally remove the overshoot for the disturbance rejection problem by using a lead-lag filter, the settling times of both transfer functions must be the same:

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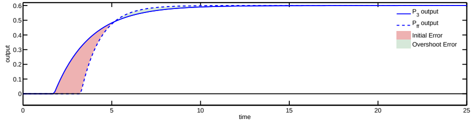
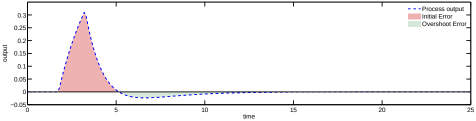
$$\tau_{ff} = \frac{4\tau_d + \lambda_d - \lambda_u}{4} = \tau_d - \frac{\lambda_b}{4}, \quad \lambda_b = \lambda_d - \lambda_u$$

Notice that the new rule for τ_{ff} implies a natural limit on performance. If parameter τ_{ff} is chosen larger, performance will only get worse because of a late compensation. The only reasons why τ_{ff} should be even larger is to decrease the control signal peak:

$$\tau_{ff} = \tau_d - \frac{\lambda_b}{4}$$





Nominal feedforward design: non-realizable delay

So, considering the IAE rule obtained for the first approach, two tuning rules are available:

$$\tau_{ff} = \frac{4\tau_d + \lambda_d - \lambda_u}{4} = \tau_d - \frac{\lambda_b}{4}$$

$$\tau_{ff} = \tau_d - \frac{\lambda_u - \lambda_d}{1.7} = \tau_d - \frac{\lambda_b}{1.7}$$

And a third one (a more agreessive rule) can be calculated to minimize Integral Squared Error (ISE) instead of IAE such as proposed in the first approach.

ISE minimization:

$$
\begin{aligned}
\text{ISE} &= \int_{\lambda_b}^{\infty} \left(e^{-\frac{(t-\lambda_b)}{\tau_{ff}}} - e^{-\frac{t}{\tau_d}} \right)^2 dt \\
&= \int_{\lambda_b}^{\infty} \left(e^{-\frac{2(t-\lambda_b)}{\tau_{ff}}} - 2e^{-\frac{\tau_d(t-\lambda_b)+\tau_{ff}t}{\tau_d\tau_{ff}}} + e^{-\frac{2t}{\tau_d}} \right) dt \\
&= -\frac{\tau_{ff}}{2} \left[e^{-\frac{2(t-\lambda_b)}{\tau_{ff}}} \right]_{\lambda_b}^{\infty} + 2\frac{\tau_d\tau_{ff}}{\tau_d+\tau_{ff}} \left[e^{-\frac{\tau_d(t-\lambda_b)+\tau_{ff}t}{\tau_d\tau_{ff}}} \right]_{\lambda_b}^{\infty} - \frac{\tau_d}{2} \left[e^{-\frac{2t}{\tau_d}} \right]_{\lambda_b}^{\infty} \\
&= \frac{\tau_{ff}}{2} - 2\tau_d \frac{\tau_{ff}}{\tau_d+\tau_{ff}} e^{-\frac{\lambda_b}{\tau_d}} + \frac{\tau_d}{2} e^{-\frac{2\lambda_b}{\tau_d}}
\end{aligned}
$$

ISE minimization:

$$\frac{d\,\text{ISE}}{d\,\tau_{ff}} = \frac{1}{2} - 2\tau_d e^{-\frac{\lambda_b}{\tau_d}} \left(\frac{1}{\tau_d + \tau_{ff}} + \frac{-\tau_{ff}}{(\tau_d + \tau_{ff})^2} \right) = \frac{1}{2} - \frac{2\tau_d^2}{(\tau_d + \tau_{ff})^2} e^{-\frac{\lambda_b}{\tau_d}} = 0$$

$$\tau_{ff}^2 + 2\tau_d\tau_{ff} + \tau_d^2(1 - 4e^{-\frac{\lambda_b}{\tau_d}}) = 0$$

$$\tau_{ff} = \frac{-2\tau_d + \sqrt{4\tau_d^2 - 4\tau_d^2(1 - 4e^{-\frac{\lambda_b}{\tau_d}})}}{2} = \tau_d \left(2\sqrt{e^{-\frac{\lambda_b}{\tau_d}}} - 1 \right)$$

Thus, three tuning rules are available:

$$\tau_{ff} = \tau_d - \frac{\lambda_b}{4}$$
$$\tau_{ff} = \tau_d - \frac{\lambda_b}{1.7}$$
$$\tau_{ff} = \tau_d \left(2\sqrt{e^{-\frac{\lambda_b}{\tau_d}}} - 1 \right)$$

which can be generalized as:

$$\tau_{ff} = \tau_d - \frac{\lambda_b}{\alpha}$$

Second approach: Guideline summary

1. Set $\beta_{ff} = \tau_u$, $\kappa_{ff} = k_d/k_u$ and calculate τ_{ff} as:

$$\tau_{ff} = \begin{cases} \tau_d & \lambda_b \leq 0 \\ \tau_d - \frac{\lambda_b}{\alpha} & 0 < \lambda_b < 4\tau_d \\ 0 & \lambda_b \geq 4\tau_d \end{cases}$$

2. Determine τ_{ff} with $\lambda_b/\tau_d < \alpha < \infty$ using:

$$\alpha = \begin{cases} \dfrac{\lambda_b}{2\tau_d\left(1-\sqrt{e^{-\lambda_b/\tau_d}}\right)} & \text{aggressive (ISE minimization)} \\ 1.7 & \text{moderate (IAE minimization)} \\ 4 & \text{conservative (Overshoot removal)} \end{cases}$$

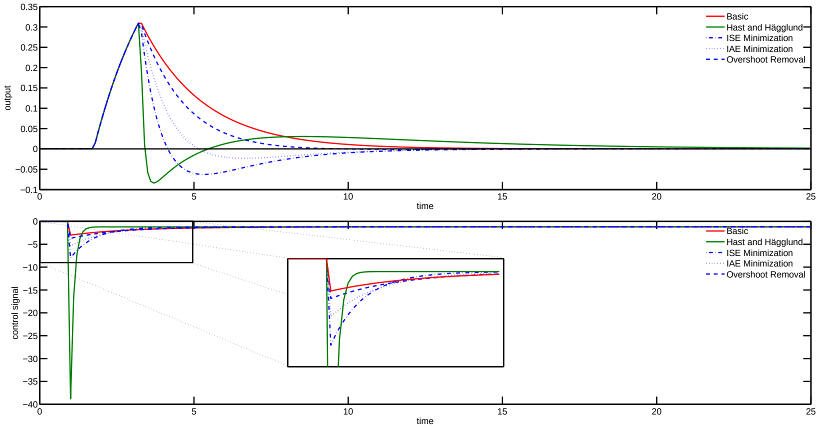
Nominal feedforward design: non-realizable delay

Example:

$$P_u(s) = \frac{0.5}{5s+1}e^{-2.25s}, \quad P_d(s) = \frac{1}{2s+1}e^{-0.75s}$$

The feedback controller is tuned using the AMIGO rule, which gives the parameters $\kappa_{fb} = 0.9$ and $\tau_i = 4.53$.

Nominal feedforward design: non-realizable delay



Nominal feedforward design: non-realizable delay

	ISE	IAE	u_{init}	J_1	J_2
Hast and Hägglund	**0.0739**	0.6423	38.7800	2.5710	0.8979
ISE Minimization	0.0896	0.6021	8.0090	0.9993	0.8615
IAE Minimization	0.0975	**0.5641**	5.3680	**0.9113**	**0.8315**
Overshoot Removal	0.1277	0.6833	**3.6920**	0.9323	0.8870

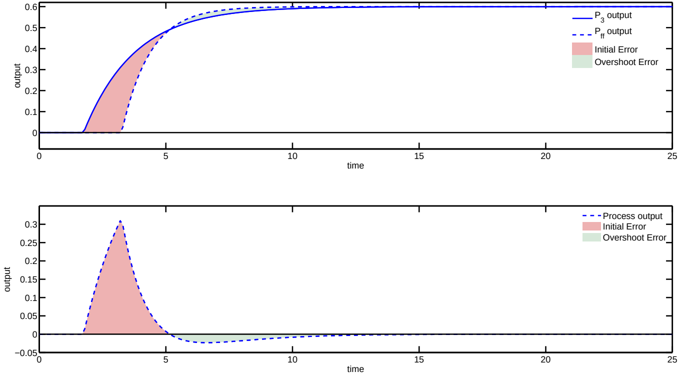
$$J_1(F,B) = \frac{1}{2}\left(\frac{\text{ISE}(F)}{\text{ISE}(B)} + \frac{\text{ISC}(F)}{\text{ISC}(B)}\right), \quad \text{ISC} = \int_0^\infty u(t)^2\,\mathrm{d}t$$

$$J_2(F,B) = \frac{1}{2}\left(\frac{\text{IAE}(F)}{\text{IAE}(B)} + \frac{\text{IAC}(F)}{\text{IAC}(B)}\right), \quad \text{IAC} = \int_0^\infty |u(t)|\,\mathrm{d}t$$

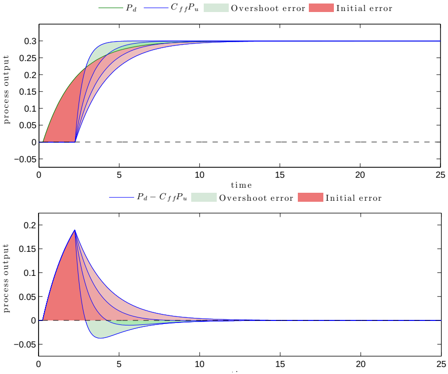
Second approach: A switching solution

It is clear that if the compensation is made too fast, the output will suffer a bigger overshoot error, while if it is too slow, the compensator will take too much time to reject the disturbance and it will have a bigger residual error. Therefore, a switching rule can be proposed in such a way that the feedforward compensator reacts fast before the outputs cross in order to decrease the residual error, and slower after this time to avoid the overshoot because of the residual error.

Second approach: A switching solution

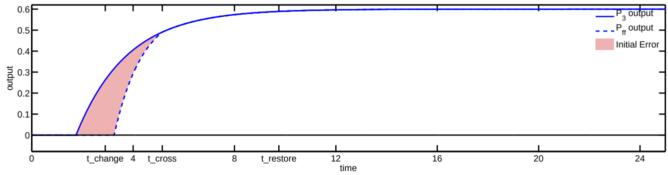


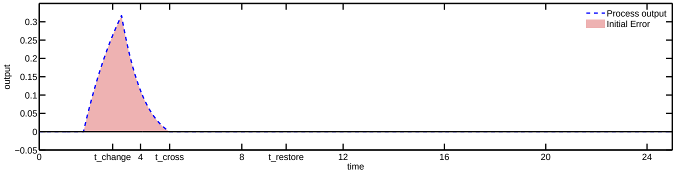
Second approach: A switching solution



$$y = P_{ff} = \left(P_d - C_{ff}P_u\right)d$$

Second approach: A switching solution





Second approach: A switching solution

The idea is to set τ_{ff} to a small value until the time when the responses of both transfer functions cross. After this time, the new value of τ_{ff} will be τ_d. Once the load disturbance is rejected, τ_{ff} will be set again to the small initial value in order to be ready for new coming disturbances.

Second approach: A switching solution

Thus, the first step is to calculate the time it takes since a step change in d appears at time instant t_d until the outputs of both transfer functions cross. This time, t_{cross}, corresponds to the point when the step responses of P_{ff} and P_d are equal:

$$\kappa_d d \left(e^{\frac{-(t_{cross}-t_d-\lambda_d)}{\tau_d}} - e^{\frac{-(t_{cross}-t_d-\lambda_u)}{\tau_{ff}}} \right) = 0$$

where it is straightforward to see that:

$$t_{cross} = \frac{\tau_d \lambda_u - \tau_{ff} \lambda_d}{\tau_d - \tau_{ff}} + t_d$$

Nominal feedforward design: non-realizable delay

Second approach: A switching solution

On the other hand, notice that the time event of the switching rule is really given at $t_{change} = t_{cross} - \lambda_u$.

Once the disturbance has been rejected, the feedforward switching controller should return to its original value in order to be ready for possible new coming load disturbances. This change must be done at a time instant, t_r, which can be proposed as the settling time of process P_d such as follows:

$$t_r = 4\tau_d + \lambda_d + t_d$$

Thus, τ_{ff} should be equal to τ_d when $t_d + t_{cross} - \lambda_u \leq t \leq t_d + t_r$ and it must be tuned for a faster response otherwise, specially for $t < t_{change}$.

Second approach: A switching solution

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Nominal feedforward design: non-realizable delay

Second approach: A switching solution

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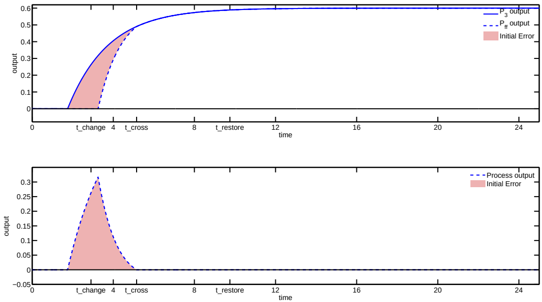
Thus, τ_{ff} should be equal to τ_d when $t_d + t_{cross} - \lambda_u \leq t \leq t_d + t_r$ and it must be tuned for a faster response otherwise, specially for $t < t_{change}$.



$$t_{cross} = \frac{\tau_d \lambda_u - \tau_{ff} \lambda_d}{\tau_d - \tau_{ff}} + t_d \qquad t_{change} = t_{cross} - \lambda_u$$

$$t_r = 4\tau_d + \lambda_d + t_d$$

Nominal feedforward design: non-realizable delay

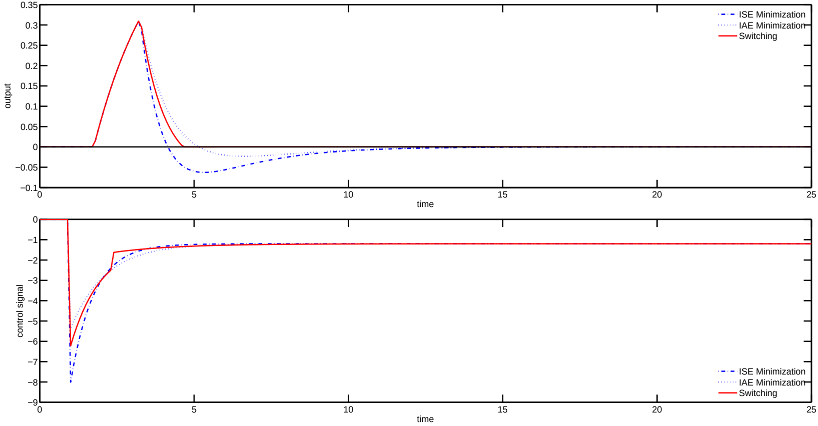
Second approach: the switching solution guideline

1. Set τ_{ff} to a value as close to 0 as possible (tradeoff with the control signal peak).
2. Wait until a step load disturbance is detected at time instant t_d. Define t_{cross} and $t_{restore}$. Set t_{change} = $t_{cross} - \lambda_u$.
3. Using a non-interacting scheme, set C_{ff} and H as follows:

$$C_{ff}(s) = \begin{cases} \dfrac{\kappa_d}{\kappa_u}\dfrac{1+\tau_u s}{1+\tau_d s} & t_{change} \leq t \leq t_r \\[2ex] \dfrac{\kappa_d}{\kappa_u}\dfrac{1+\tau_u s}{1+\tau_{ff} s} & \text{otherwise} \end{cases}$$

4. Go to step 2.

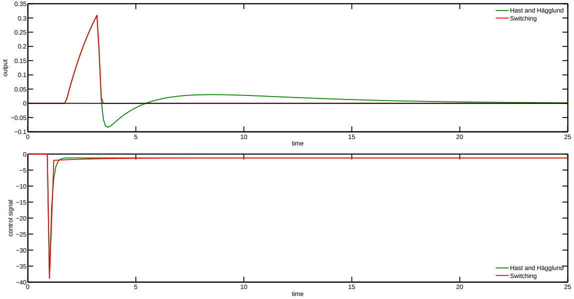
Nominal feedforward design: non-realizable delay



Nominal feedforward design: non-realizable delay

	ISE	IAE	u_{init}	J_1	J_2
ISE Minimization	0.0896	0.6021	8.0090	0.9993	0.8615
IAE Minimization	0.0975	0.5641	**5.3680**	0.9113	0.8315
Switching	**0.0889**	**0.4252**	6.2160	**0.9062**	**0.7527**

Nominal feedforward design: non-realizable delay



	ISE	IAE	u_{init}	J_1	J_2
Hast and Hägglund	0.0739	0.6423	38.78	**2.5710**	0.8979
Switching	**0.0630**	**0.2878**	38.78	2.6650	**0.7149**

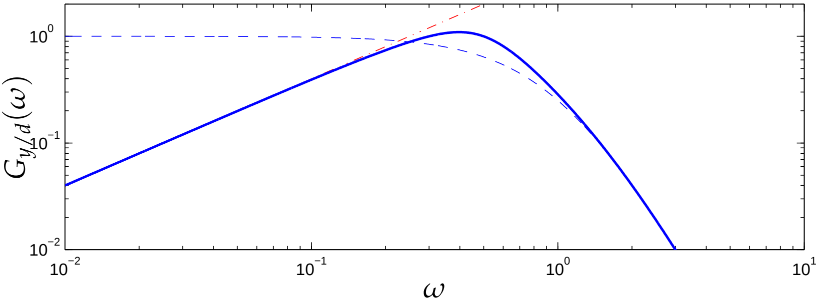
Outline

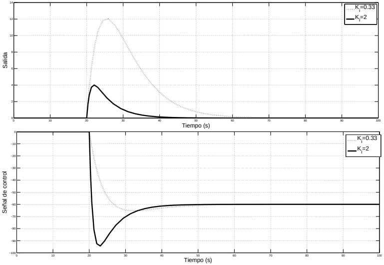
There exist metrics to evaluate feedback controllers for load disturbance rejection problem based on the controller parameters. For instance:

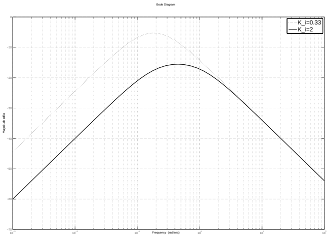
$$G_{y/d} = \frac{P_u(s)}{1 + C_{fb}(s)P_u(s)} = \frac{C_{fb}(s)P_u(s)}{1 + C_{fb}(s)P_u(s)}\frac{1}{C_{fb}(s)} \quad \omega \downarrow\downarrow$$

$$G_{y/d} \approx \frac{1}{C_{fb}(s)} \approx \frac{s}{\kappa_i}$$

Performance indices for feedforward control




Salida
Tiempo (s)
Señal de control
Tiempo (s)
K_i=0.33
K_i=2
K_i=0.33
K_i=2


Bode Diagram
K_i=0.33
K_i=2
Frequency (rad/sec)

Performance indices for feedforward control

Objective

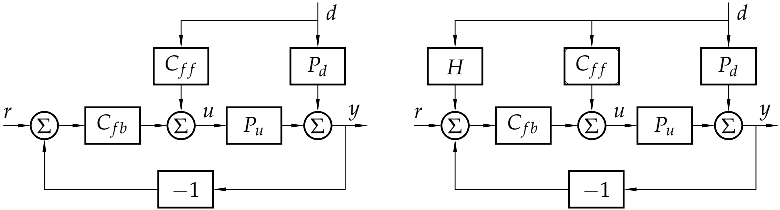
To proposed indices such that the advantage of using a feedforward compensator with respect to the use of a feedback controller only can be quantified.

Methodology

- Propose different indices
- Calculate the indices based on the process parameters

Performance indices for feedforward control

The two feedforward schemes are considered:



Performance indices for feedforward control

Assumptions:

$$P_u = \frac{\kappa_u}{1+\tau_u} e^{-s\lambda_u}, \quad P_d = \frac{\kappa_d}{1+s\tau_d} e^{-s\lambda_d}$$

Only, the non-inversion delay problem is analyzed:

$$\text{Lead-lag:} \quad C_{ff} = \frac{\kappa_d}{\kappa_u}\frac{1+s\tau_u}{1+s\tau_d}$$

Performance indices for feedforward control

Assumptions:

$$C_{fb} = \kappa_{fb}\left(1 + \frac{1}{s\tau_i}\right)$$

The lambda tuning rule is considered:

$$\kappa_{fb} = \frac{\tau_i}{\kappa_u(\lambda_u + \tau_{bc})}, \qquad \tau_i = \tau_u$$

where τ_{bc} is the closed-loop time constant.

The following index structure is proposed

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

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 $0 < I_{FF/FB} < 1$.

Calculation of IAE_{fb}

In the feedback only case, the transfer function between disturbance d and process output y is

$$G_{y/d}(s) = \frac{P_d(s)}{1 + P_u(s)C_{fb}(s)} = \frac{\kappa_d \dfrac{e^{-s\lambda_d}}{1+s\tau_d}}{1 + \kappa_u \dfrac{e^{-s\lambda_u}}{1+s\tau_u} \kappa_{fb} \dfrac{1+s\tau_i}{s\tau_i}}$$

Assuming that $r = 0$ and d is a step with magnitude A_d and using the final value theorem, the Integrated Error (IE) value becomes (note that $e = -y$, with $r = 0$)

$$IE_{FB} = \int_0^\infty e(t)dt = \lim_{s\to 0} s \cdot \frac{1}{s} E(s) = \lim_{s\to 0} -G_{y/d}(s)\frac{A_d}{s} = -\frac{\tau_i \kappa_d}{\kappa_u \kappa_{fb}} A_d$$

Calculation of IAE_{fb}

The magnitude of the IE value can be set equal to the IAE value provided that the controller is tuned so that there are no oscillations:

$$IAE_{FB} = \frac{\tau_i \kappa_d}{\kappa_u \kappa_{fb}} A_d$$

Finally, considering the lambda tuning rule, it becomes

$$IAE_{FB} = \kappa_d A_d (\lambda_u + \tau_{bc})$$

Calculation of IAE_{FF} for classical FF scheme

In this case, the transfer function from the disturbance to the error is

$$G_{y/d}(s) = -\frac{P_d(s) + P_u(s)C_{ff}(s)}{1 + P_u(s)C_{fb}(s)} = \frac{\kappa_d \dfrac{e^{-s\lambda_d}}{1+s\tau_d} - \kappa_d \dfrac{e^{-s\lambda_u}}{1+s\tau_d}}{1 + \kappa_u \dfrac{e^{-s\lambda_u}}{1+s\tau_u} \kappa_{fb} \dfrac{1+s\tau_i}{s\tau_i}}$$

Considering the lambda tuning rule and that the delays are approximated as

$$e^{-\lambda_u s} \cong 1 - \lambda_u s, \qquad e^{-\lambda_d s} \cong 1 - \lambda_d s$$

It results in:

$$G_{y/d}(s) = -\frac{\kappa_d(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)s^2}{(1+\tau_d s)(1+\tau_{bc}s)}$$

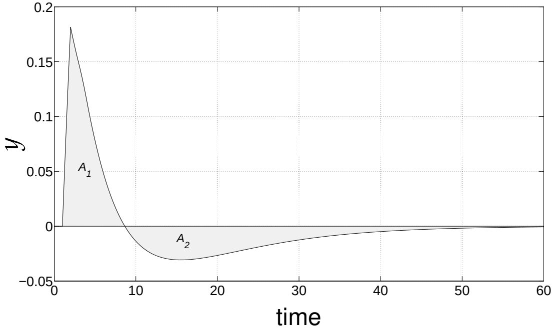
Calculation of IAE_{FF} for classical FF scheme

The IE value for this case becomes

$$IE_{FF} = \int_0^\infty e(t)dt = \lim_{s\to 0} s \cdot \frac{1}{s} G_{y/d}(s) \frac{A_d}{s} = 0.$$

which demonstrates that zero steady-state error can be achieved by using feedforward control.

Calculation of IAE_{FF} for classical FF scheme



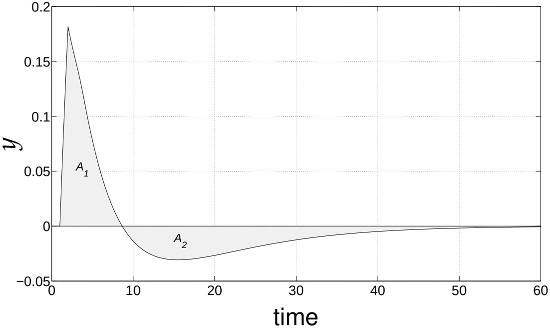
Calculation of IAE_{FF} for classical FF scheme

Now, it is worth determining the expression of the error in the time domain when a step signal of amplitude A_d is applied as a disturbance. We have

$$e(t) = \begin{cases} \dfrac{\kappa_d A_d(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)}{\tau_{bc}\tau_d(\tau_{bc} - \tau_d)} \left(\tau_d e^{-t/\tau_{bc}} - \tau_{bc} e^{-t/\tau_d}\right) & \tau_{bc} \neq \tau_d \\ \dfrac{\kappa_d A_d(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)}{\tau_d^2} \left(1 - \dfrac{t}{\tau_d}\right) e^{-t/\tau_d} & \tau_{bc} = \tau_d \end{cases}$$

Performance indices for feedforward control

Calculation of IAE_{FF} for classical FF scheme



$$t_0 = \begin{cases} \dfrac{\tau_{bc}\tau_d}{\tau_{bc}-\tau_d}\log\left(\frac{\tau_{bc}}{\tau_d}\right) & \tau_{bc} \neq \tau_d \\ \tau_d & \tau_{bc} = \tau_d \end{cases}$$

Calculation of IAE_{FF} for classical FF scheme

We can therefore calculate the area of the first part of the transient as

$$A_1 = \int_0^{t_0} e(t)dt = \begin{cases} \dfrac{\kappa_d A_d}{\tau_d}(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)\left(\dfrac{\tau_{bc}}{\tau_d}\right)^{-\dfrac{\tau_{bc}}{\tau_{bc}-\tau_d}} & \tau_{bc} \neq \tau_d \\ \dfrac{\kappa_d A_d}{\tau_d}(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)e^{-1} & \tau_{bc} = \tau_d \end{cases}$$

Performance indices for feedforward control

According to

$$IE_{FF} = \int_0^\infty e(t)dt = \lim_{s\to 0} s \cdot \frac{1}{s} G_{y/d}(s) \frac{A_d}{s} = 0.$$

the area $|A_2|$ in the previous figure is equal to $|A_1|$, and the IAE value can finally be determined as

$$IAE_{FF} = 2|A_1| = \begin{cases} 2\frac{\kappa_d A_d}{\tau_d}(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)\left(\frac{\tau_{bc}}{\tau_d}\right)^{-\frac{\tau_{bc}}{\tau_{bc}-\tau_d}} & \tau_{bc} \neq \tau_d \\ 2\frac{\kappa_d A_d}{\tau_d}(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)e^{-1} & \tau_{bc} = \tau_d \end{cases}$$

Calculation of IAE_{FF} for non-interacting FF scheme

In this case, the IAE_{FF} estimation can be obtained in a straightforward manner, as the effect from the feedback controller is removed.

The IAE result obtained in the non-invertible delay case can be reformulated as

$$
\begin{aligned}
IAE_{FF} &= \kappa_d A_d \left((\lambda_u - \lambda_d) - (\tau_d - \tau_u - \tau_u + \tau_u) \left(1 - 2e^{-\frac{\lambda_u - \lambda_d}{\tau_d - \tau_u - \tau_u + \tau_u}} \right) \right) \\
&= \kappa_d A_d \left(1 - \frac{\tau_d - \tau_u - \tau_u + \tau_u}{\lambda_u - \lambda_d} \left(1 - 2e^{-\frac{\lambda_u - \lambda_d}{\tau_d - \tau_u - \tau_u + \tau_u}} \right) \right) (\lambda_u - \lambda_d) \\
&= \kappa_d A_d \left(1 - \frac{1}{a} + \frac{2}{a} e^{-a} \right) (\lambda_u - \lambda_d) \\
&= \kappa_d A_d \alpha (\lambda_u - \lambda_d)
\end{aligned}
$$

where

$$
\alpha = 1 - \frac{1}{a} + \frac{2}{a} e^{-a}, \;\; a = \frac{\lambda_u - \lambda_d}{\tau_d - \tau_u - \tau_u + \tau_u}
$$

Analysis and discussion on the indices

- Feedback control without feedforward:

$$IAE_{FB} = \kappa_d A_d(\lambda_u + \tau_{bc})$$

- Feedforward with classical control scheme and classical tuning:

$$IAE_{FF} = 2\frac{\kappa_d A_d}{\tau}(\lambda_u + \tau_{bc})(\lambda_u - \lambda_d)f(\tau_{bc}/\tau_d) \tag{1}$$

where

$$f(\tau_{bc}/\tau_d) = \begin{cases} \left(\dfrac{\tau_{bc}}{\tau_d}\right)^{-\dfrac{\tau_{bc}}{\tau_{bc}-\tau_d}} & \tau_{bc} \neq \tau_d \\ e^{-1} & \tau_{bc} = \tau_d \end{cases} \tag{2}$$

- Feedforward with non-interacting control scheme:

$$IAE_{FF} = \alpha\kappa_d A_d(\lambda_u - \lambda_d)$$

where α can vary based on the τ_{ff} value.

Performance indices for feedforward control

Analysis and discussion on the indices

The ratio between the IAE value of the classical scheme and the noninteracting scheme is

$$\frac{IAE_{\text{classical}}}{IAE_{\text{noninteracting}}} = \frac{2(\lambda_u + \tau_{bc}) f(\tau_{bc}/\tau_d)}{\tau_d \alpha}$$

Therefore, the classical scheme gives a smaller IAE value when

$$\tau_d > \frac{2(\lambda_u + \tau_{bc}) f(\tau_{bc}/\tau_d)}{\alpha}$$

Index interpretation

For the classical feedforward control case, the index becomes

$$I_{FF/FB} = 1 - \frac{IAE_{FF}}{IAE_{FB}} = 1 - \frac{2(\lambda_u - \lambda_d)}{\tau_d} f(\tau_{bc}/\tau_d)$$

For the noninteracting feedforward control scheme, the index is given by

$$I_{FF/FB} = 1 - \frac{IAE_{FF}}{IAE_{FB}} = 1 - \frac{\alpha(\lambda_u - \lambda_d)}{\lambda_u + \tau_{bc}}$$

Example 1

$$P_u(s) = \frac{e^{-2s}}{10s+1} \qquad P_d(s) = \frac{e^{-s}}{5s+1}$$

Using lambda tuning with $\tau_{bc} = \tau_u = 10$ gives the PI controller parameters $\kappa_{fb} = 0.83$ and $\tau_i = 10$.

The feedforward compensators are defined as

$$C_{ff}(s) = \frac{10s+1}{5s+1}$$

for the classical feedforward control scheme and as

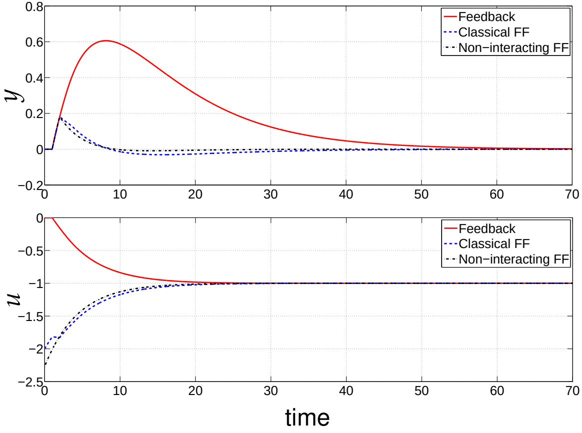
$$C_{ff} = \frac{10s+1}{4.4s+1}$$

for the non-interacting feedforward control scheme (to minimize IAE).

Example 1

Control scheme	IAE^r	IAE^e	$I_{FF/FB}$
Feedback	11.99	12	–
Classical FF	1.21	1.2	0.9
Non-interacting FF	0.63	0.63	0.95

Example 1



y
u
time
Feedback
Classical FF
Non−interacting FF
0.8
0.6
0.4
0.2
0
−0.2
−0.5
−1
−1.5
−2
−2.5
0
10
20
30
40
50
60
70

Example 2

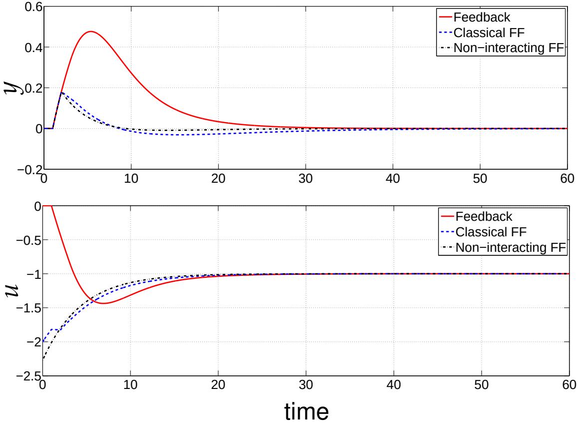
The differences between the pure feedback scheme and the feedforward schemes can be reduced by retuning the PI controller to obtain a more aggressive response. Lets retune the PI controller only for the case when pure feedback is used, by using $\tau_{bc} = 0.25\tau_u$.

Performance indices for feedforward control

Example 2

Control scheme	IAE^r	IAE^e	$I_{FF/FB}$
Feedback	4.5	4.5	–
Classical FF	1.21	1.2	0.73
Non-interacting FF	0.63	0.63	0.86

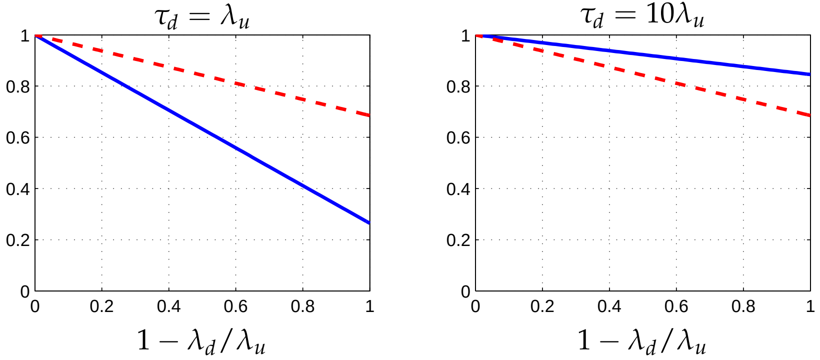
Example 2


Feedback
Classical FF
Non−interacting FF
y
0.6
0.4
0.2
0
−0.2
0
10
20
30
40
50
60
Feedback
Classical FF
Non−interacting FF
u
0
−0.5
−1
−1.5
−2
−2.5
0
10
20
30
40
50
60
time

Example 3

Assume that $\tau_{bc} = \tau_u = \lambda_u$. It means that we have a process model $P_u(s)$ where the delay is equal to the time constant and that the lambda tuning rule is used with $\tau_{bc} = \tau_u$. Two different values of the time constant $\tau_d = \eta\lambda_u$, where η = 1 or 10.

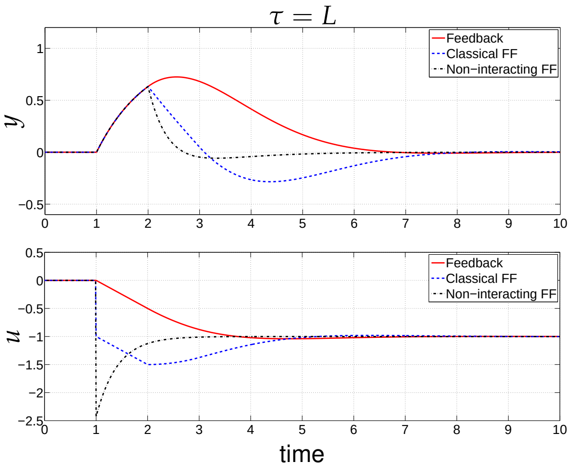
Example 3


$\tau_d = \lambda_u$
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
$1 - \lambda_d/\lambda_u$
$\tau_d = 10\lambda_u$
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
$1 - \lambda_d/\lambda_u$

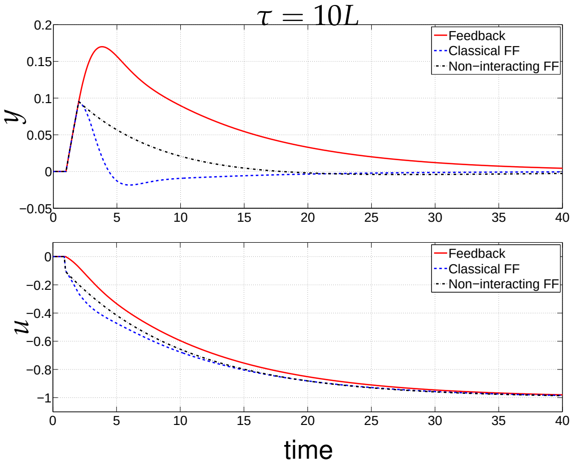
Example 3

τ_d	Control scheme	IAE^r	IAE^e	$I^r_{FF/FB}$	$I^e_{FF/FB}$
λ_u	Feedback	2.04	2.0		
	Classical FF	1.43	1.47	0.30	0.26
	Non-interacting FF	0.63	0.63	0.69	0.69
$10\lambda_u$	Feedback	2.00	2.0		
	Classical FF	0.34	0.31	0.83	0.85
	Non-interacting FF	0.63	0.63	0.69	0.69

Example 3


$\tau = L$
Feedback
Classical FF
Non−interacting FF
y
1
0.5
0
−0.5
0
1
2
3
4
5
6
7
8
9
10
Feedback
Classical FF
Non−interacting FF
u
0.5
0
−0.5
−1
−1.5
−2
−2.5
time

Example 3


$\tau = 10L$
0.2
0.15
0.1
0.05
0
−0.05
y
0
5
10
15
20
25
30
35
40
Feedback
Classical FF
Non−interacting FF
0
−0.2
−0.4
−0.6
−0.8
−1
u
time

Outline

Conclusions

- The motivation for feedforward tuning rules was introduced.
- The feedback effect on the feedforward design was analyzed.
- The different non-realizable situations were studied.
- The two available feedforward control schemes were used.
- Simple tuning rules based on the process and feedback controllers parameters were derived.
- Performance indices for feedforward control were proposed.

Conclusions

Future research

What else can be done?

- **Nominal tuning**. Unified methodology for low-order feedforward controllers tuning
- **Robust tuning**. Scale up to other feedforward structures
- **DTC with feedforward action**. Extension to MIMO processes
- **Experimental results**. Validate the theoretically claimed benefits
- **Distributed parameter systems**. Feedforward tuning rules to deal with resonance dynamics

Conclusions

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End of the presentation

Thank you for your attention