PHILIPS CTT Hogeschool van Utrecht

Systeem en Regeltechniek

FMT / Mechatronica

Deel 5: Toepassing: PID regelaarontwerp

Blok 10: Bandbreedte en verstoringsonderdrukking

Gert van Schothorst

Philips Centre for Technical Training (CTT)
Philips Centre for Industrial Technology (CFT)
Hogeschool van Utrecht - PTGroep

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Cursus Systeem en Regeltechniek

Overzicht

Deel 1	Blok 1.	Inleiding
Wo. 14-04	Blok 2.	Basisprincipes modelvorming massa-veersystemen
	Blok 3.	De regelaar als veer-demper combinatie
Deel 2	Blok 4.	Frequentie-domein beschrijving
Wo. 21-04	Blok 5.	Basisconcepten in de regeltheorie
Deel 3	Blok 6.	Verdere inleiding in de regeltheorie
Wo. 28-04	Blok 7.	De PD regelaar als veer-demper combinatie
Deel 4	Blok 8.	Stabiliteit van regelsystemen
Wo. 12-05	Blok 9.	De PID regelaar in het frequentie domein
Deel 5	Blok 10.	Bandbreedte en verstoringsonderdrukking
Wo. 19-05	Blok 11.	Toepassing: Tunen PID regelaar mechatronisch systeem
Deel 6	**Extra regeltechniek**	
Wo. 26-05		

What is the required bandwidth of a control system?

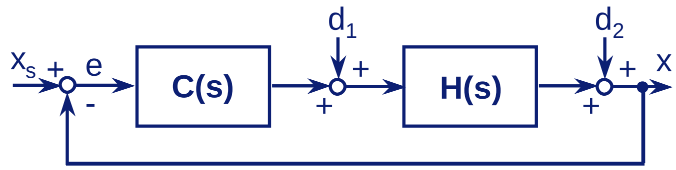
?

Recap aim of feedback...

Disturbance Suppression

Recap aim of feedback...

Feedback with disturbances:

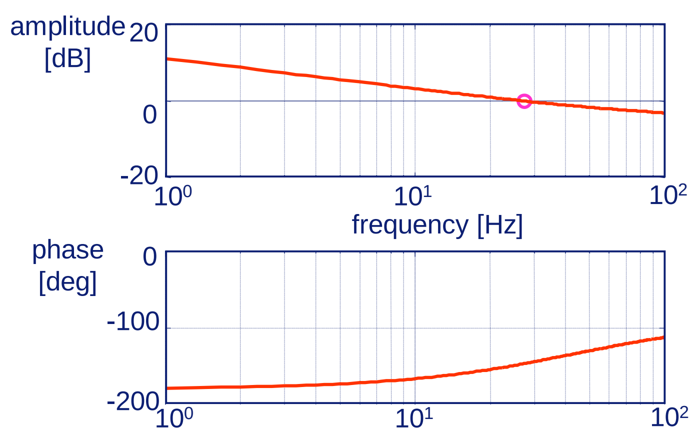


Recall: $H_c(s)=\dfrac{x(s)}{x_s(s)}=\dfrac{C(s)\cdot H(s)}{1+C(s)\cdot H(s)}$

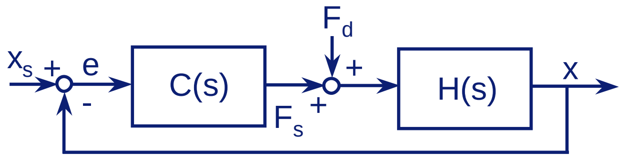
So: $x \approx x_s$ if: $C(s)\cdot H(s) >> 1$

Recap Bandwidth Definition

Bandwidth: 0 dB crossing open loop



Exercise Bandwidth Determination



Given $H(s) = \frac{1}{ms^2}$ with m = 2,5 [kg]

$F_d = \sin(2\pi ft)$ [N] with f = 1 [Hz]

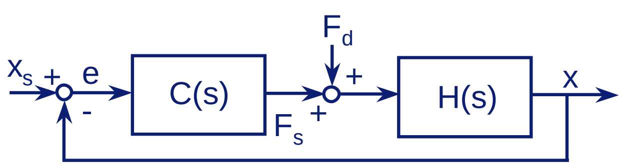
Assume $C(s) = k_p + k_v s$

Specification: $|e(t)| < 1$ [µm]

Question:

1. What is the required bandwidth?
2. If C(s) = 0, how large is $|e(t)|_{max}$?

Exercise Bandwidth Determination



Process Sensitivity: $H_{ps}(s) = \frac{x}{F_d}(s) = \frac{H(s)}{1+C(s)H(s)}$

$H(2\pi) \approx 0.01$

$H_{ps}(2\pi) < 10^{-6} \Rightarrow C(2\pi) > 10^6 \Rightarrow k_p = 10^6$

Bandwidth: $C(\omega_b)H(\omega_b) = 0$ dB $\Rightarrow k_p / (2\pi f_b)^2 = 1$

$\Rightarrow f_b \approx 100$ [Hz]

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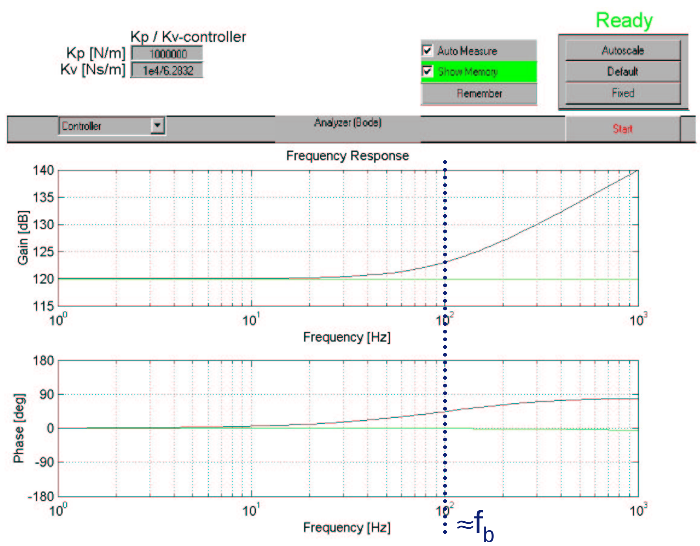
Bandwidth and disturbance suppression

K_p / K_v controller in DIET (Philips tool)



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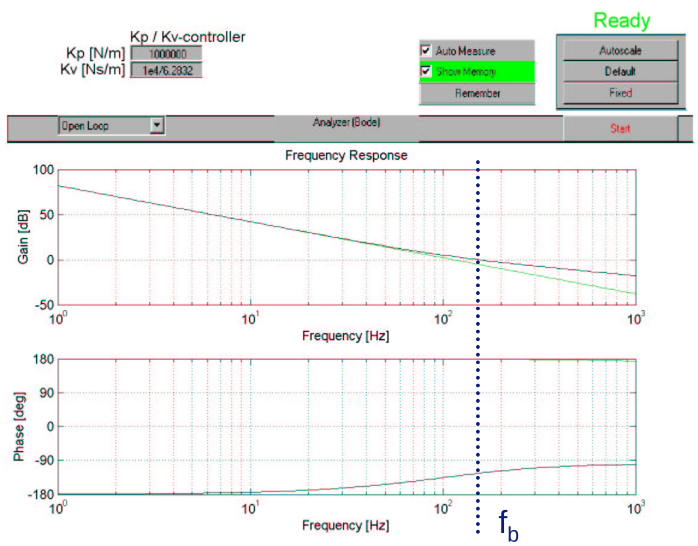
Bandwidth and disturbance suppression

Open loop in DIET (Philips tool)



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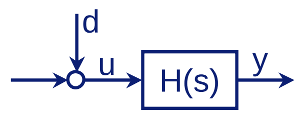
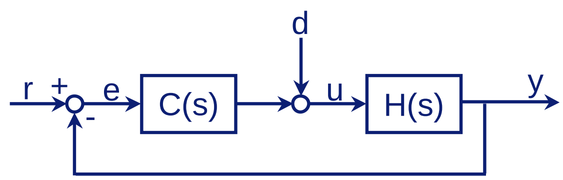
Bandwidth and disturbance suppression

Disturbance suppression

No control: $y = Hu = Hd$



Closed-loop control:



$y = Hu = Hd + HC(-y) \quad \Leftrightarrow \quad y = \frac{H}{1+CH} d$

Below bandwidth: CH >> 1

$$y = \frac{H}{1+CH} d \approx \frac{H}{CH} d \approx \frac{1}{C} d \quad \rightarrow \quad y = 0$$

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Bandwidth and disturbance suppression

Disturbance suppression

No control: $y_o = Hd$

Closed-loop: $y_c = \frac{H}{1+CH} d$

$$\frac{y_c}{y_o} = \frac{1}{1+CH} = S$$

Benefit of feedback = Sensitivity function

Example: $H = 0.01$; $CH = 10^4$; $d = 1$

$y_o = 0.01$

$S \approx 10^{-4}$

$y_c = \frac{0.01}{1+10^4} 1 \approx 10^{-6}$

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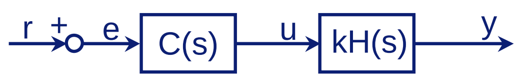
Bandwidth and disturbance suppression

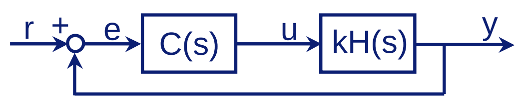
Robustness

Open-loop:

$$y = kHu = kHCr$$



Closed-loop:



$$y = kHu = kHCr - kHCy \quad \Leftrightarrow \quad y = \frac{kCH}{1+kCH} r$$

Below bandwidth: CH >> 1

$$y = \frac{kCH}{1+kCH} r \approx \frac{kCH}{kCH} r \approx r$$

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Bandwidth and disturbance suppression

Robustness

Open-loop: $y_o = kHCr$

Relative change: $\dfrac{y_o - \bar{y}_o}{\bar{y}_o} = \dfrac{kHCr - HCr}{HCr} = k - 1$

Closed-loop: $y_c = \dfrac{kCH}{1+kCH} r$

Relative change: $\dfrac{y_c - \bar{y}_c}{\bar{y}_c} = \dfrac{\frac{kCH}{1+kCH} r - \frac{CH}{1+CH} r}{\frac{CH}{1+CH} r} = \dfrac{k-1}{1+kCH}$

$$\frac{\frac{y_c - \bar{y}_c}{\bar{y}_c}}{\frac{y_o - \bar{y}_o}{\bar{y}_o}} = \frac{\frac{k-1}{1+kCH}}{k-1} = \frac{1}{1+kCH} = S$$

Benefit of feedback
= Sensitivity function

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Bandwidth and disturbance suppression

Robustness

Example: $CH = 10^4$, $k = 1.1$

$$\frac{y_o - \bar{y}_o}{\bar{y}_o} = k - 1 = 0.1$$

$S \approx 10^{-4}$

$$\frac{y_c - \bar{y}_c}{\bar{y}_c} = \frac{k-1}{1+kCH} = \frac{0.1}{1+1.1\ 10^4} = 9.1\ 10^{-6} \approx 10^{-5}$$

Conclusion:

OK if S<1, bad if S>1

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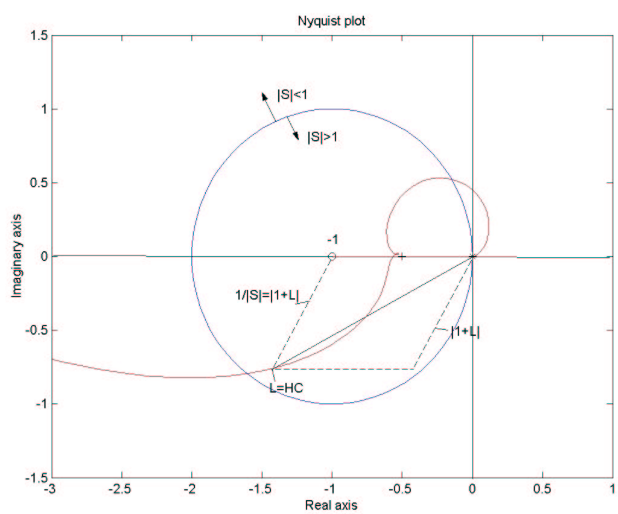
Bandwidth and disturbance suppression

Robustness and Nyquist



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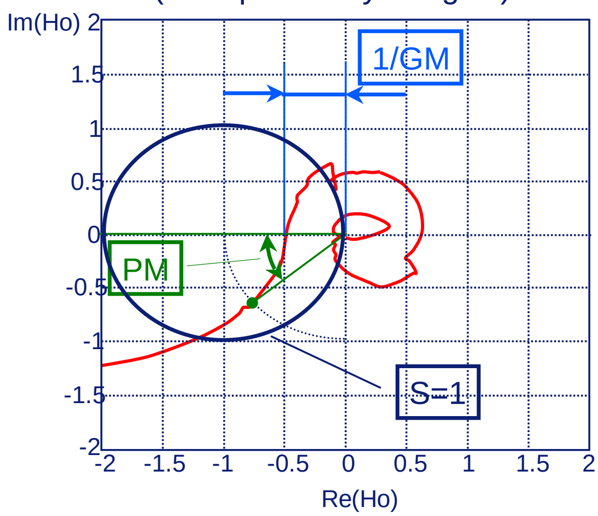
Bandwidth and disturbance suppression

Robustness and Nyquist

(Recap Stability Margins)



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Bandwidth and disturbance suppression

Design for performance

$S(j\omega) << 1$

However:

Area where S<1 equals area where S>1

Bode sensitivity integral

(holds if at least two more poles than zeros)

Hence:

Design controller such that S is low where most important disturbances occur

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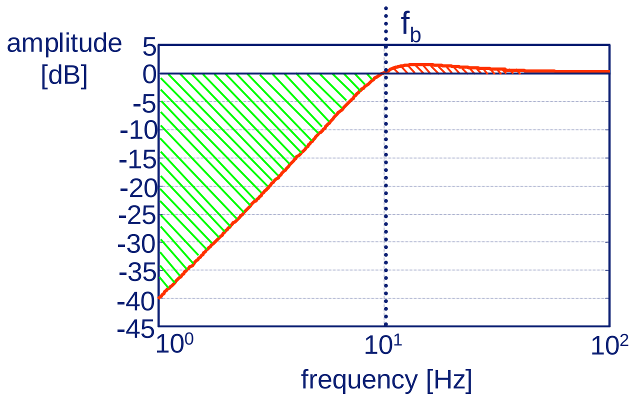
Bandwidth and disturbance suppression

Design for performance

Bode Sensitivity Integral



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Bandwidth and disturbance suppression

Loop Shaping Procedure

1. Stabilize the plant:
   Add lead/lag with zero = BW/3 and pole = BW*3, adjust gain to set stability or add a pure PD with breakpoint at the BW.
2. Add low-pass filter:
   Choose poles = BW*6.
3. Add notch, if necessary, or apply any other kind of first or second order filter and shape the loop.
4. Add integral action:
   Choose zero = BW/5.
5. Increase BW:
   Increase gain and adapt zeros/poles of integral action, lead/lag and other filters.

During steps 2-5: check all relevant transfer functions and relate to disturbance spectrum.

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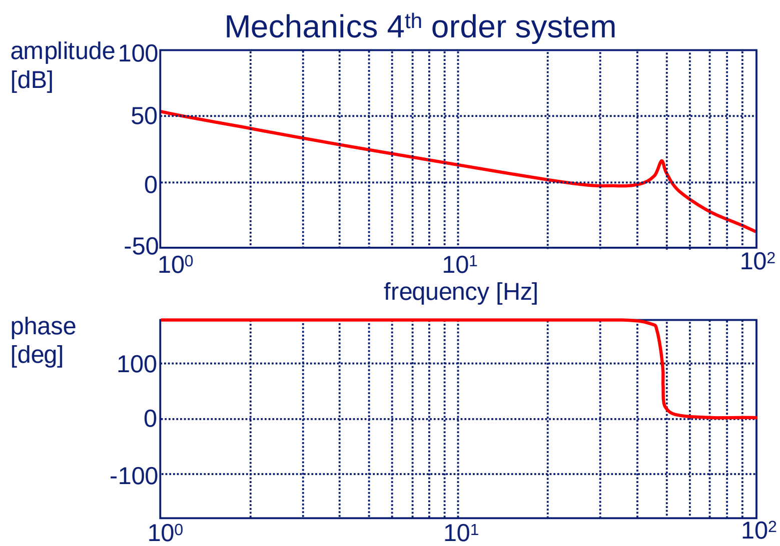
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system



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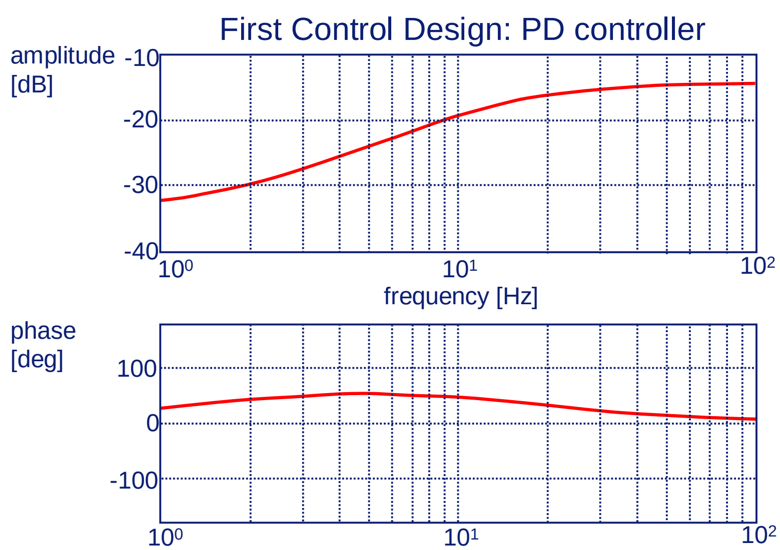
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system



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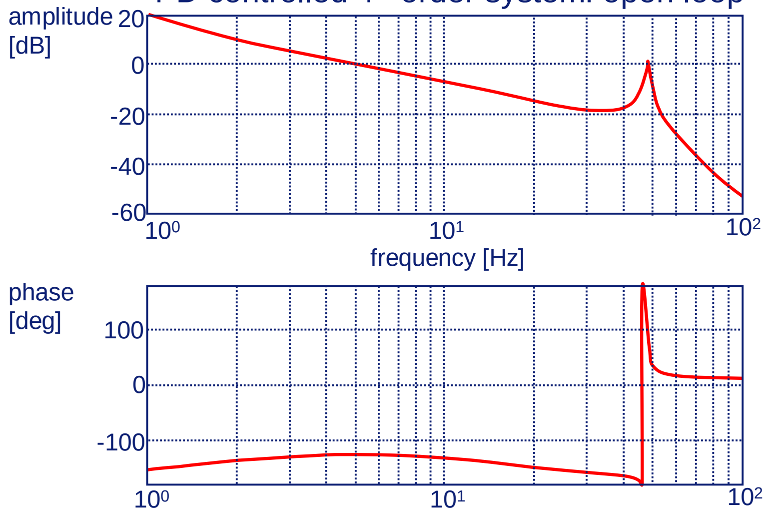
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

PD controlled 4th order system: open loop



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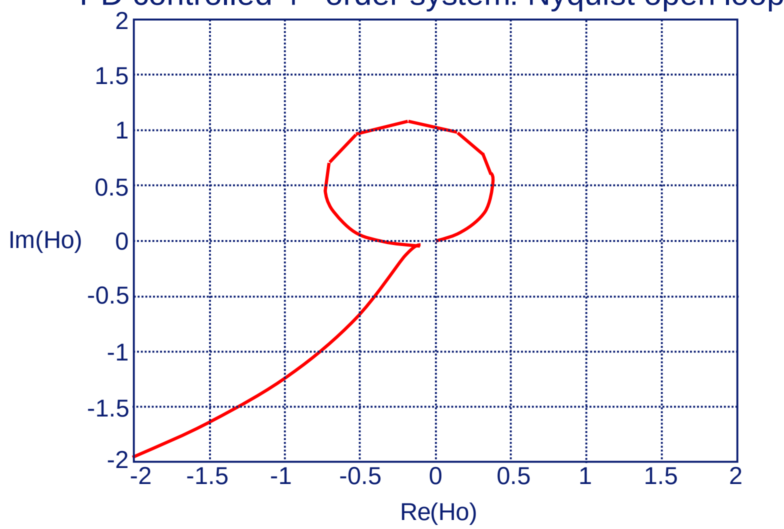
Loop Shaping Example - 4th order system

PD controlled 4th order system: Nyquist open loop



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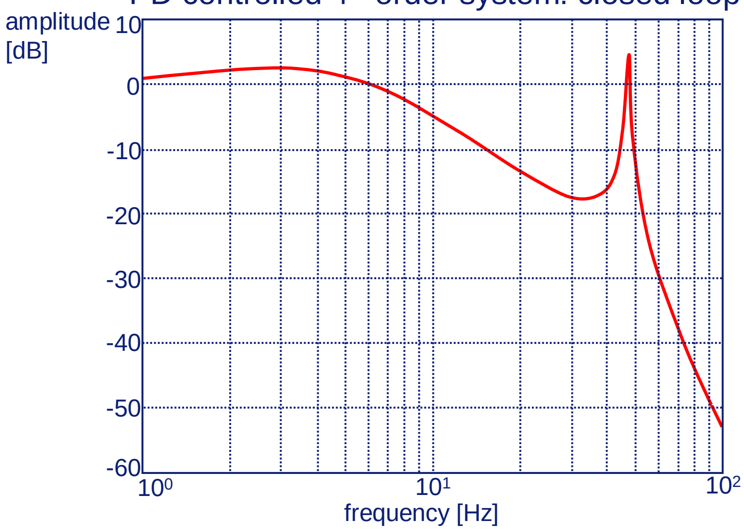
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

PD controlled 4th order system: closed loop



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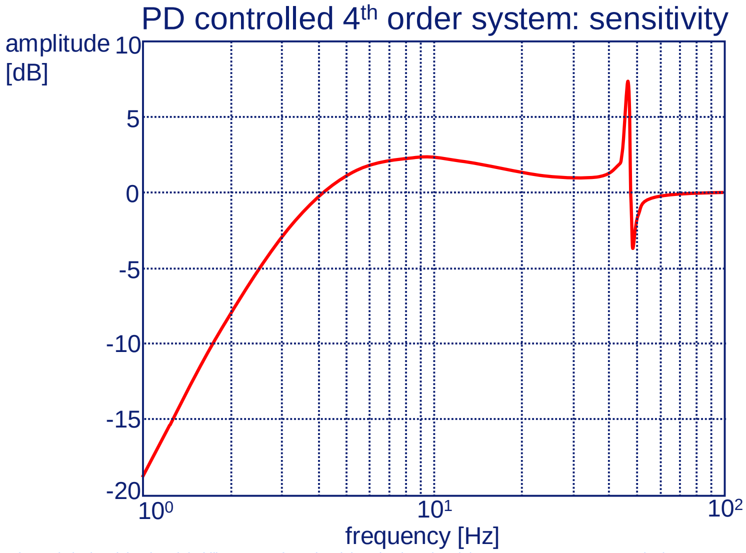
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

PD controlled 4th order system: sensitivity



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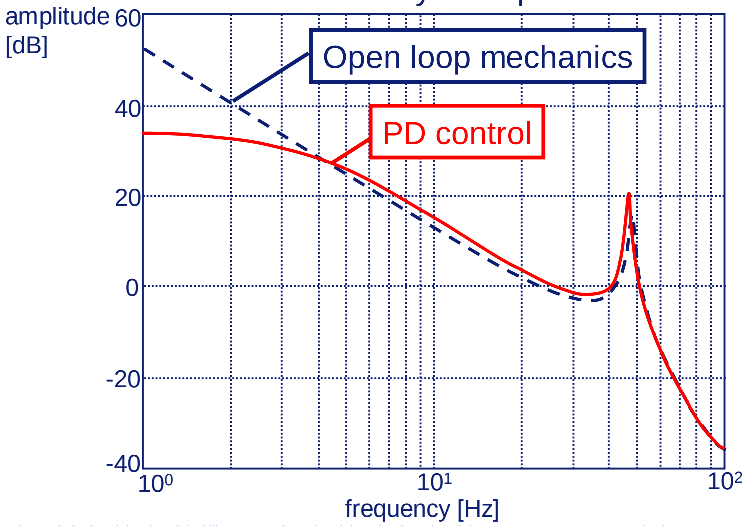
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

PD controlled 4th order system: process sensitivity



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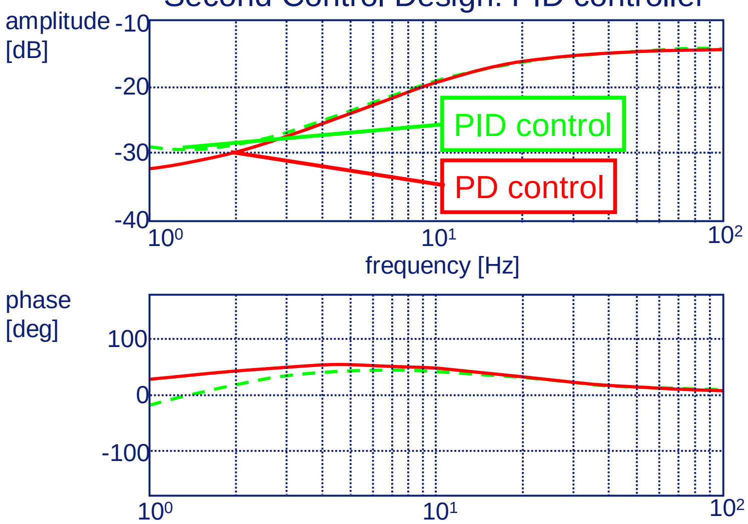
Loop Shaping Example - 4th order system

Second Control Design: PID controller



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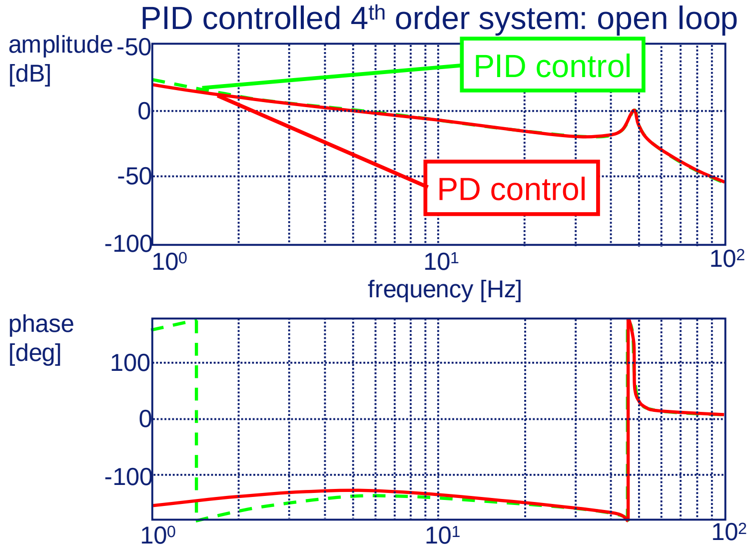
Bandwidth and disturbance suppression

Loop Shaping Example - 4^{th} order system

PID controlled 4^{th} order system: open loop



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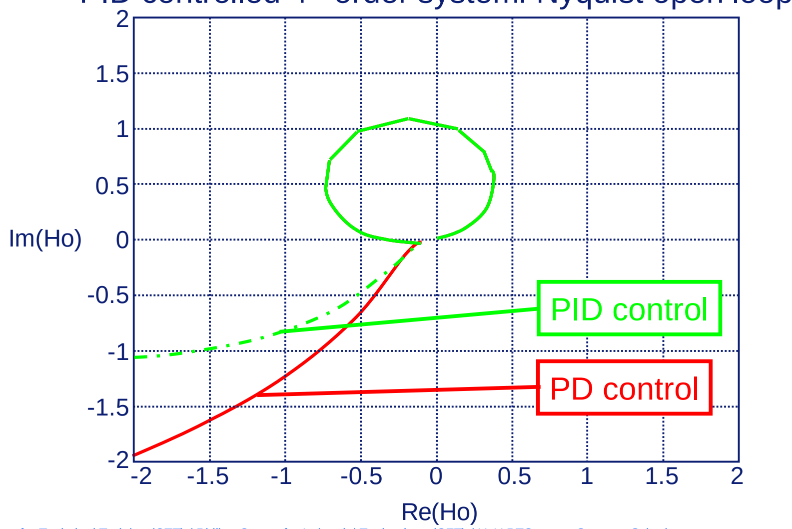
Bandwidth and disturbance suppression

Loop Shaping Example - 4^{th} order system

PID controlled 4^{th} order system: Nyquist open loop



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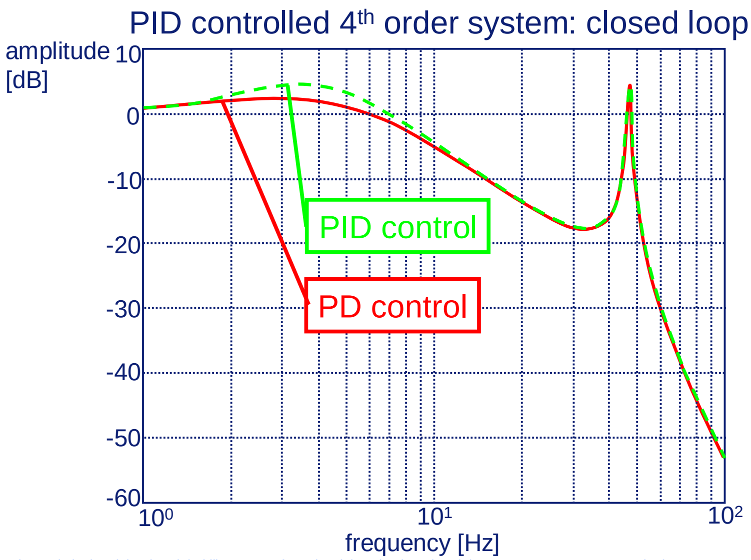
Loop Shaping Example - 4th order system



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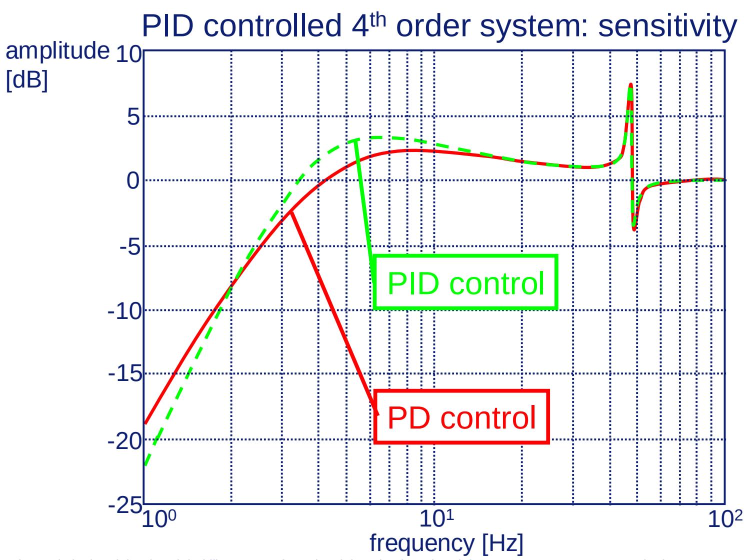
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system



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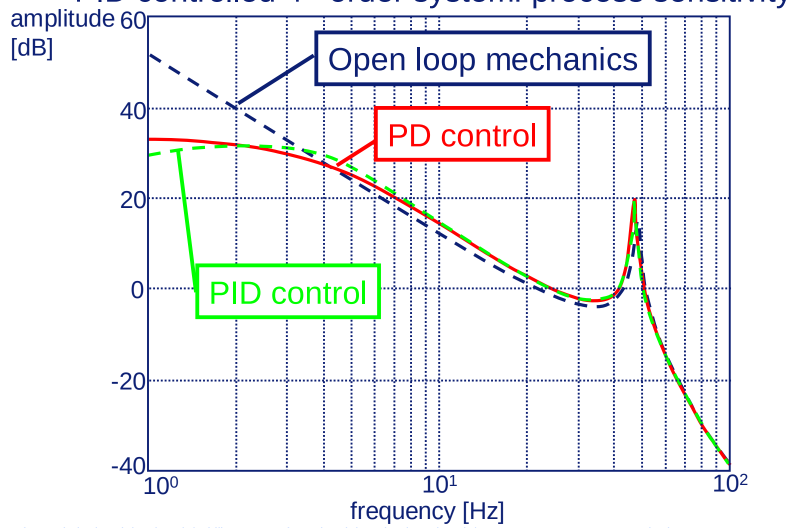
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

PID controlled 4th order system: process sensitivity



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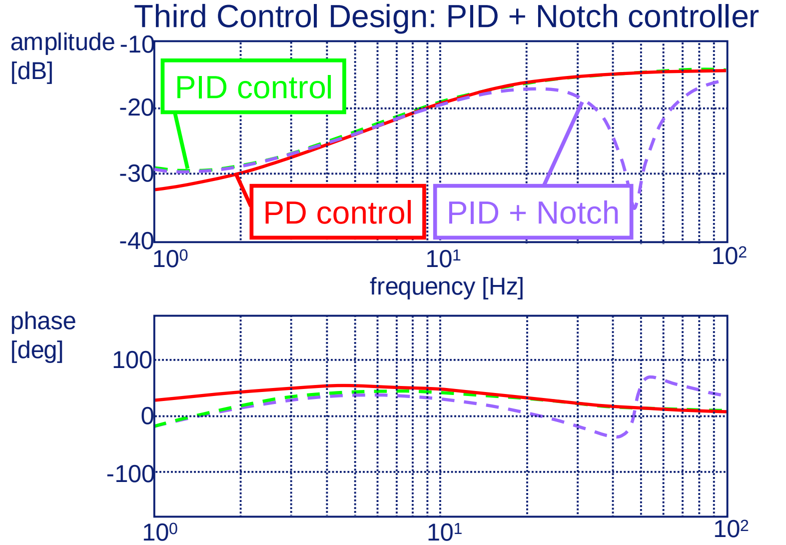
Loop Shaping Example - 4th order system

Third Control Design: PID + Notch controller



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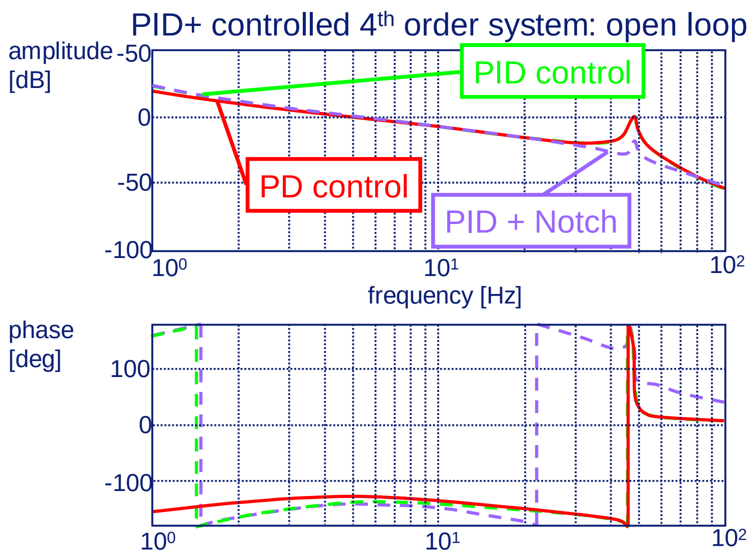
Bandwidth and disturbance suppression

Loop Shaping Example - 4^{th} order system



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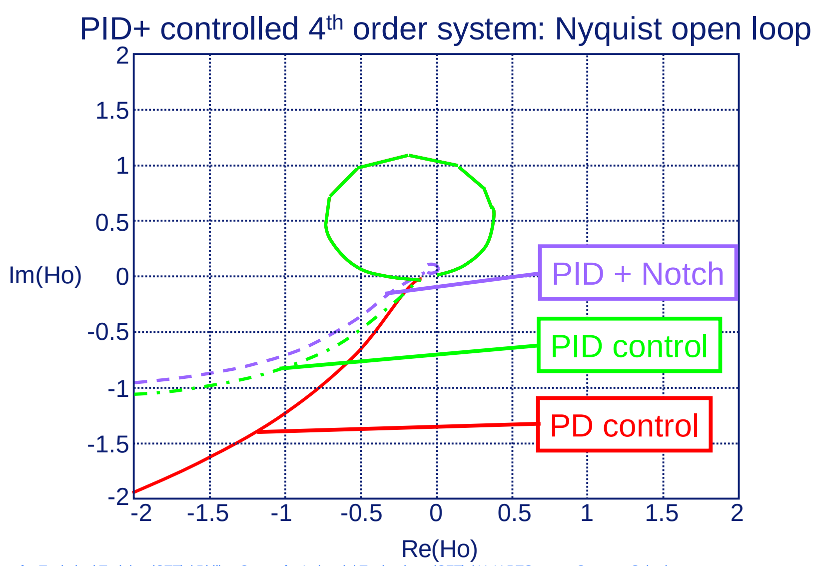
Bandwidth and disturbance suppression

Loop Shaping Example - 4^{th} order system



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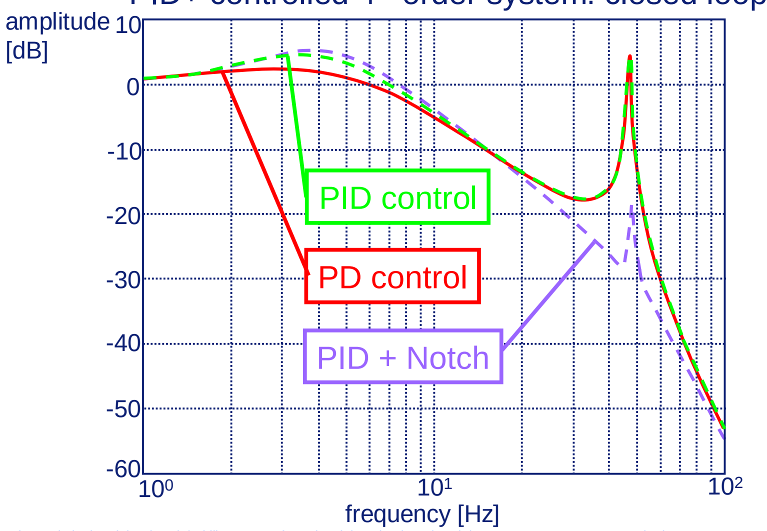
Loop Shaping Example - 4th order system

PID+ controlled 4th order system: closed loop



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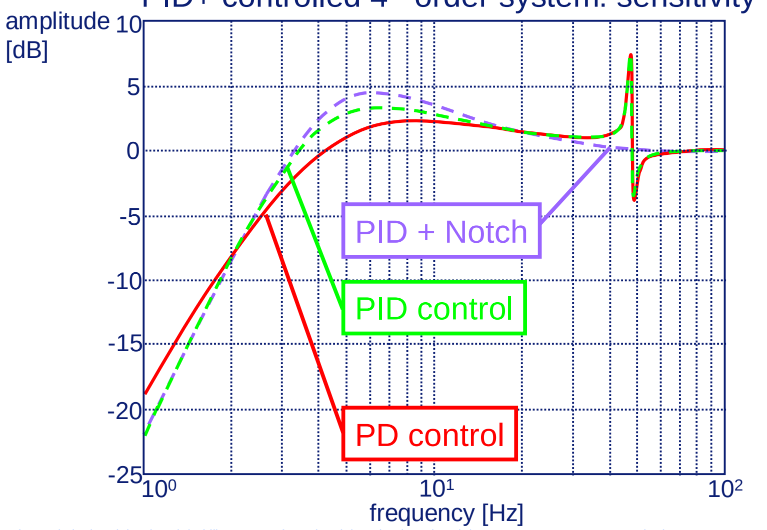
Loop Shaping Example - 4th order system

PID+ controlled 4th order system: sensitivity



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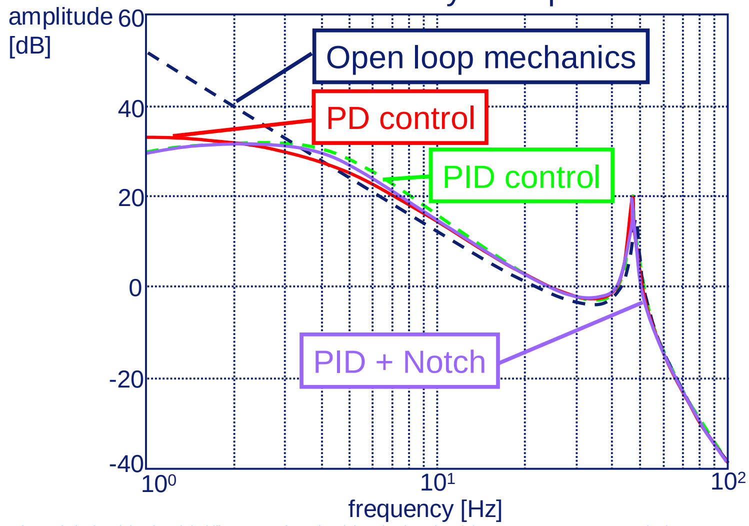
Loop Shaping Example - 4th order system

PID+ controlled 4th order system: process sensitivity



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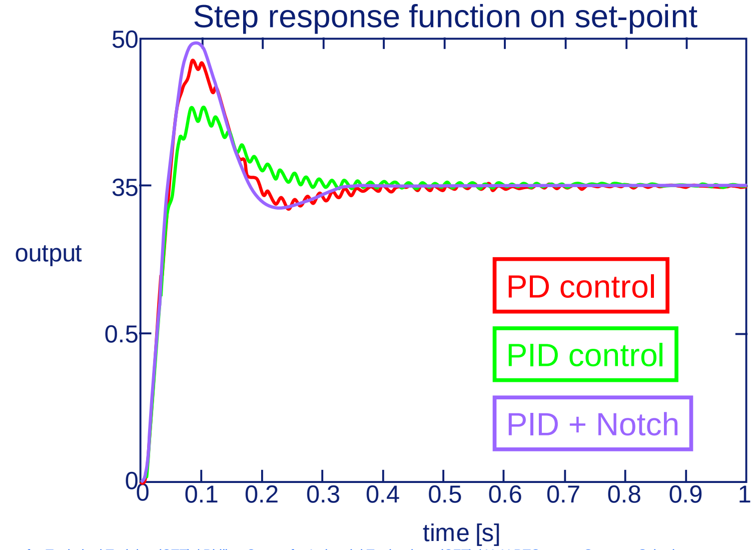
Bandwidth and disturbance suppression

Loop Shaping Example - 4th order system

Step response function on set-point



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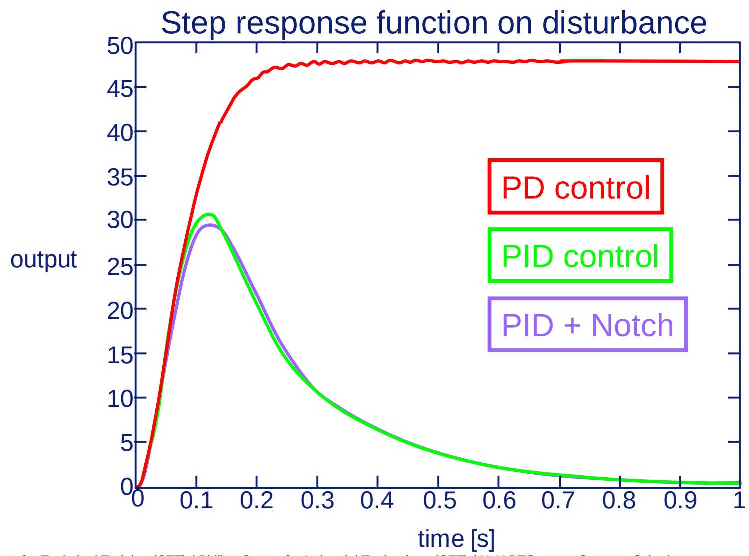
Loop Shaping Example - 4^{th} order system



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Bandwidth and disturbance suppression

Summary

- Aim of feedback
  - Disturbance suppression
  - Robustness
- Benefit of feedback = sensitivity function S
- Design for performance:
  - S small where disturbances occur
  - High bandwidth - small S for low frequency
- Loop shaping procedure

Exercise with 20-sim