Modeling for Control

Training Session 4: Feedback & feedforward control

COC

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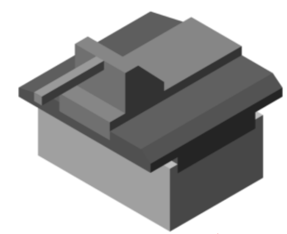
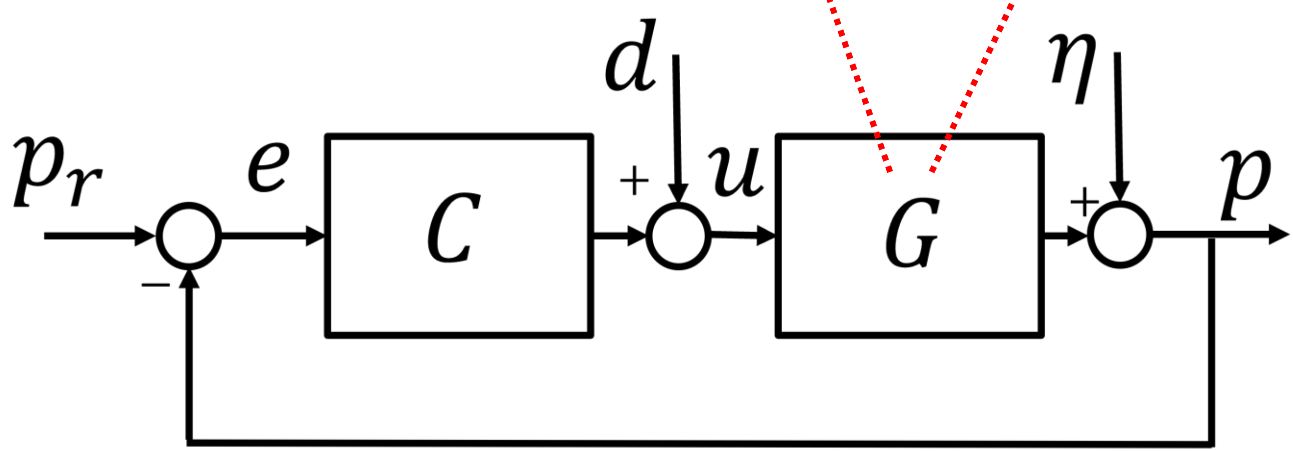
FEEDBACK CONTROL

Motion control system (without feedforward control)

- p_r: reference position
- p: encoder position
- e: error
- d: external disturbance
- η: measurement noise
- u: motor input

- G: plant
- C: feedback controller

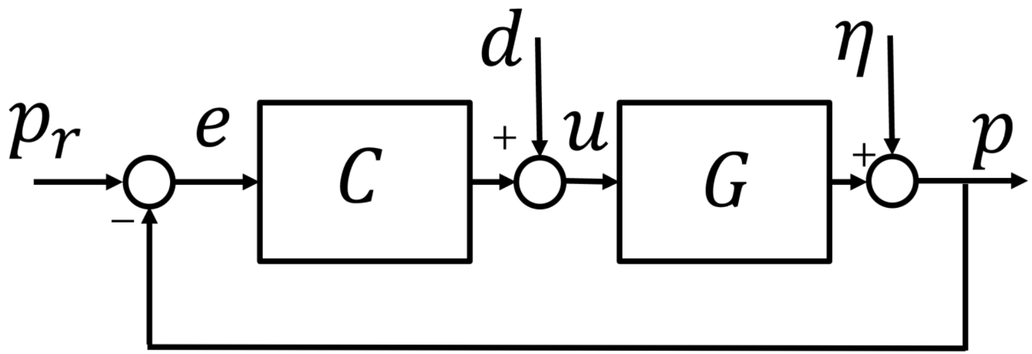




How to design for closed-loop performance?

- Open loop: $L = G \cdot C$
- Closed-loop transfer-functions:

1. Sensitivity: $S := \frac{e}{p_r} = \frac{u}{d} = \frac{1}{1+L}$
2. Complementary sensitivity: $\mathrm{T} := \frac{p}{p_r} = \frac{p}{\eta} = \frac{L}{1+L}$
3. Process sensitivity: $GS := \frac{p}{d} = \frac{G}{1+L}$
4. Control sensitivity: $\mathrm{CS} := \frac{u}{p_r} = \frac{C}{1+L}$



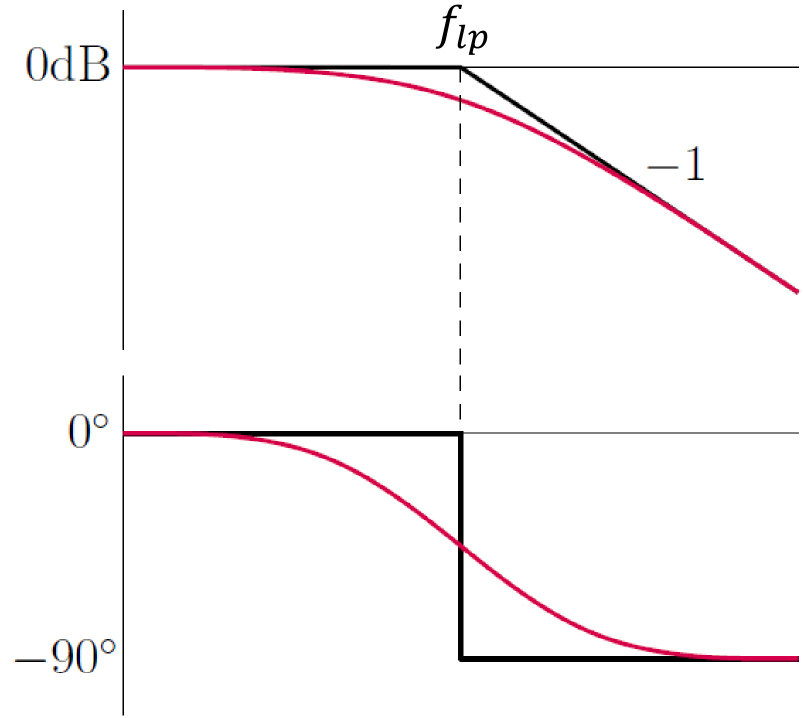
Feedback controller design: general rules of thumb

- Typical controller structure: $C = P \cdot \underbrace{\left(1 + \frac{2\pi f_i}{s}\right)}_{\mathrm{I}} \cdot \underbrace{\frac{1+\frac{s}{2\pi f_{lead}}}{1+\frac{s}{2\pi f_{lag}}}}_{\mathrm{D}}$

- General tuning procedure:
  1. Select desired control bandwidth f_{bw} *(0dB magnitude-point in open-loop),*
  2. Set proportional gain $P = \frac{1}{3}\frac{1}{|G|_{@f_{bw}}}$,
  3. The derivative-action should start at frequency $f_{lead} = \frac{f_{bw}}{3}$ and end at frequency $f_{lag} = 3f_{bw}$,
  4. The integrator action should stop before the start of the lead-action, typically at frequency $f_i = \frac{f_{bw}}{10}$ or $f_i = \frac{f_{bw}}{5}$.

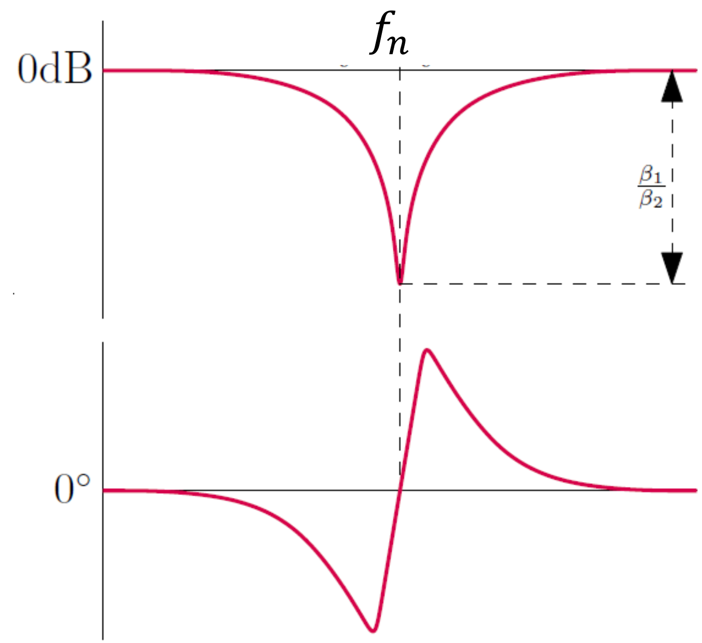
Feedback controller design: other useful control elements (1/2)

- If necessary, a first-order low-pass filter can be used to further suppress the high-frequency noise and resonance-modes:
  - $C_{lp} = \frac{1}{1+\frac{s}{2\pi f_{lp}}}$,
  - with, typically, $f_{lp} = 9f_{bw}$ or $f_{lp} = 6f_{bw}$

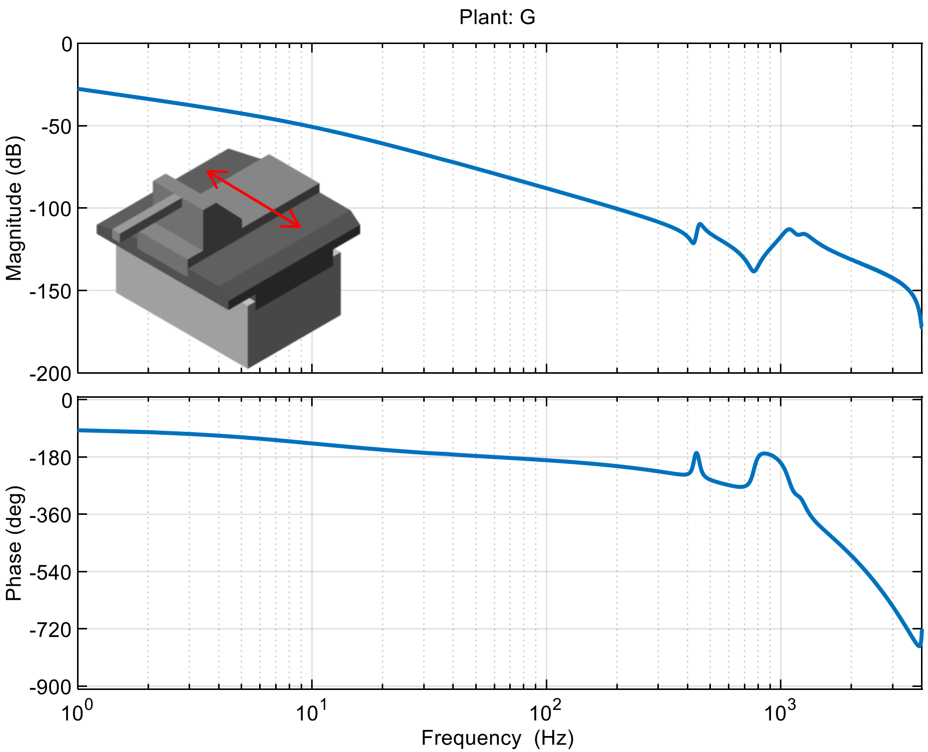


Feedback controller design: other useful control elements (2/2)

- If necessary, notch-filters can be used to selectively target specific resonance frequencies:
  - $C_n = \dfrac{\left(\frac{1}{(2\pi f_n)^2}s^2+\frac{2\beta_1}{2\pi f_n}s+1\right)}{\left(\frac{1}{(2\pi f_n)^2}s^2+\frac{2\beta_2}{2\pi f_n}s+1\right)}$,
  - with f_n the resonance frequency that we want to suppress.

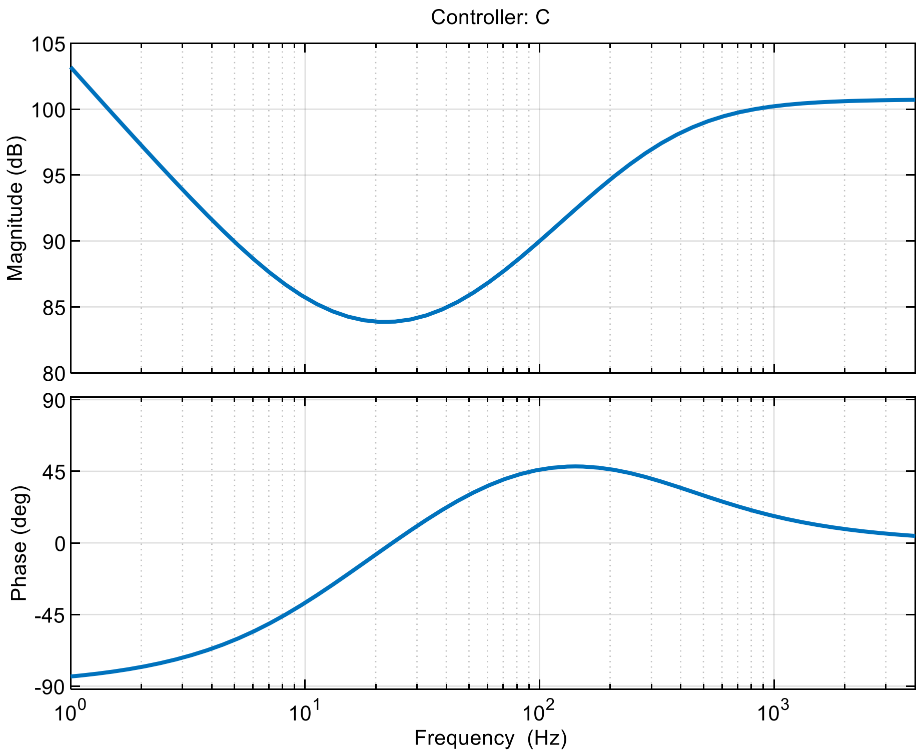


Case study: X-stage of the AB383 Simscape model



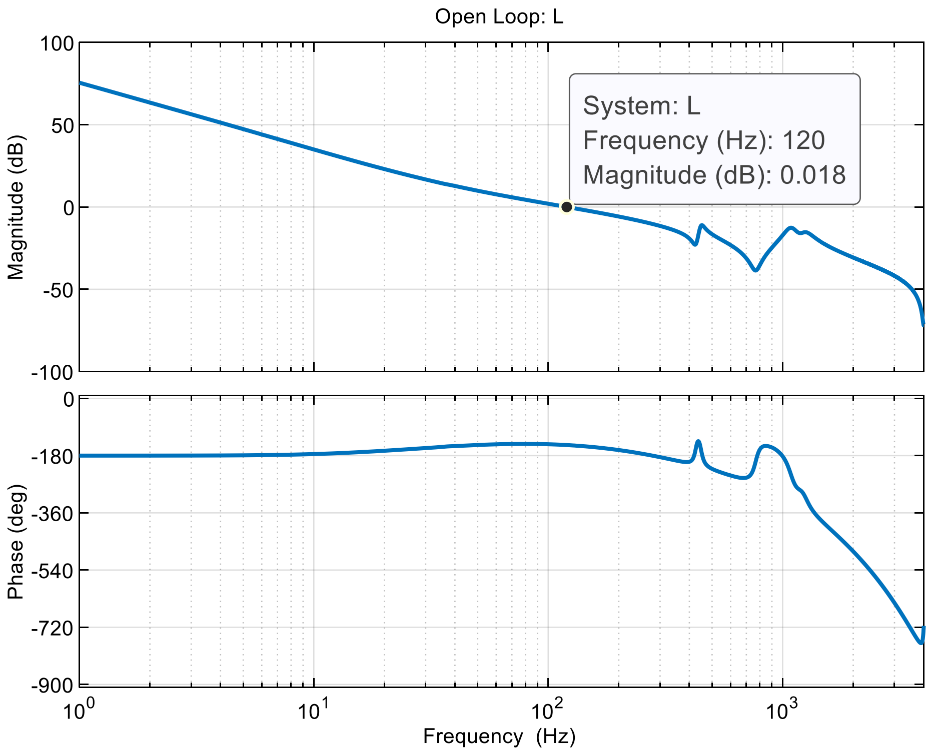
- The first clearly visible resonance frequency lays at 452 Hz.
- The time-delay results in a phase loss linearly related to the frequency.
- The combination of flexible dynamics and phase loss caused by time-delay results in a limited obtainable bandwidth.
- Let us try to tune an open loop bandwidth $f_{bw} = 120 \text{ Hz}.$

Case study: feedback controller C



- $C = P \cdot \left(1 + \frac{2\pi f_i}{s}\right) \cdot \frac{1+\frac{s}{2\pi f_{lead}}}{1+\frac{s}{2\pi f_{lag}}}$
- Gain:
  - $|G|_{@120\ Hz} = \text{db2mag}(-91.2)$
  - $\text{P} = \frac{1}{3}\frac{1}{|G|_{@f_{bw}}} = 11982$
- Lead/lag:
  - $f_{lead} = \frac{f_{bw}}{3} = 40\ \text{Hz}$
  - $f_{lag} = 3f_{bw} = 360\ \text{Hz}$
- Integrator:
  - $f_i = \frac{f_{bw}}{10} = 12\ \text{Hz}$
- Total controller:
  - $C = 11982 \cdot \left(1 + \frac{75.4}{s}\right) \cdot \frac{1+0.004019s}{1+0.0004421s}$

Case study: open loop L

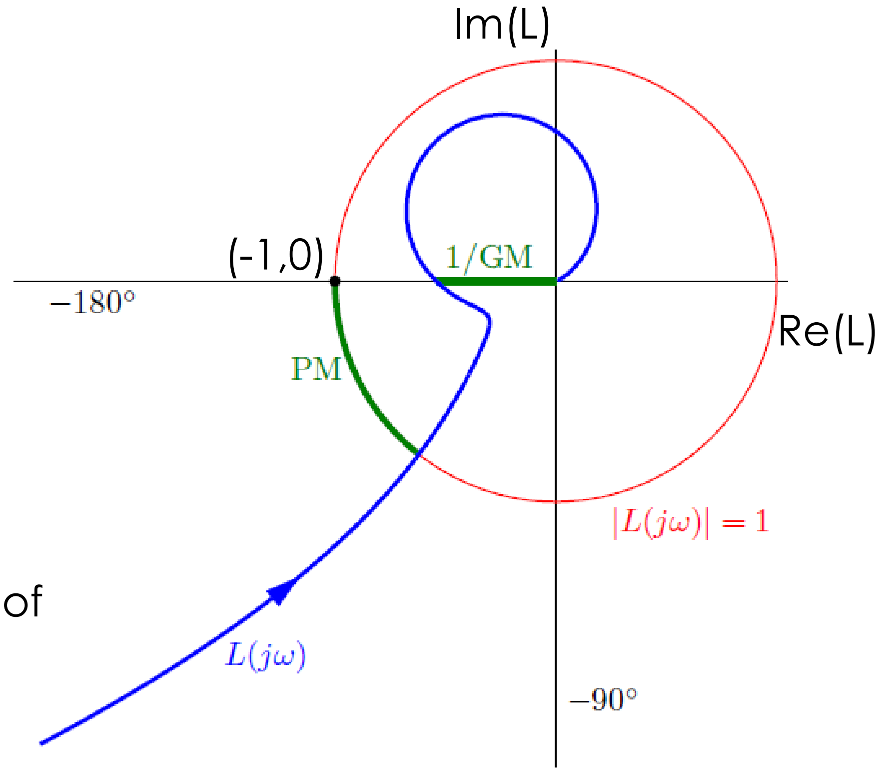


- Open loop: $L = G \cdot C$.
- Open loop bandwidth is 120 Hz, as desired.

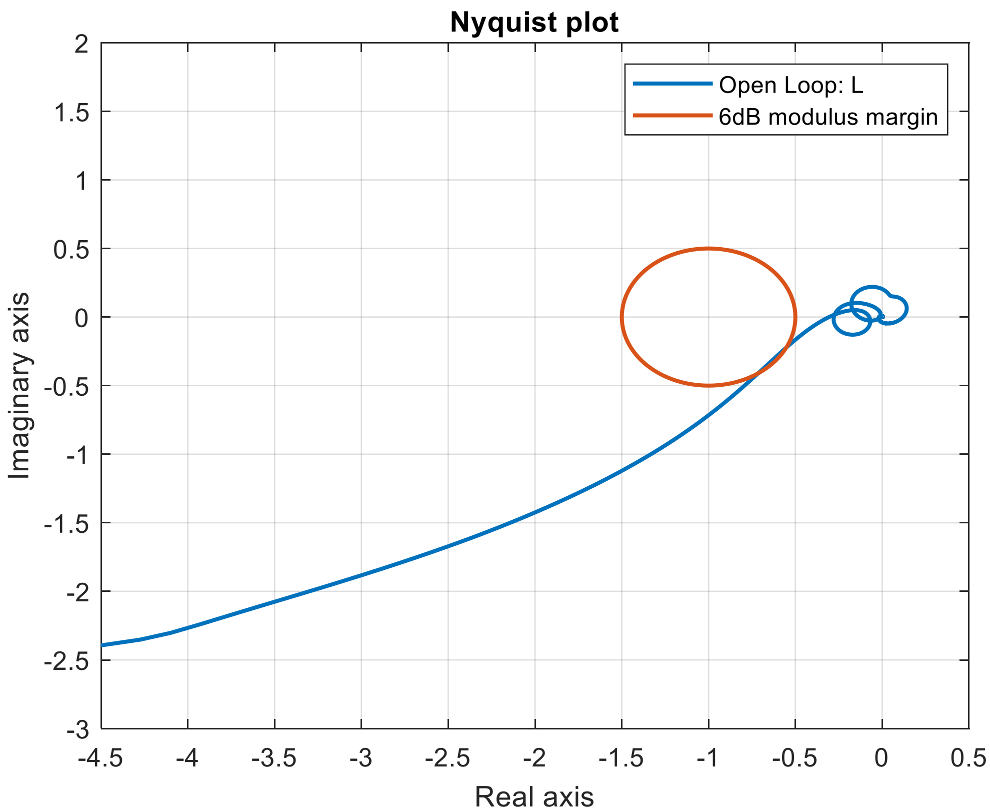
- The next step is to check if the controller is indeed stable.

Intermezzo: Nyquist Stability Criterion

- The Nyquist Stability Criterion can be used to asses closed-loop stability:
  - graphical check
  - Based on frequency-response function (FRF) of the plant, i.e. mechanical spectrum
- Nyquist plot:
  - Re(L) on horizontal axis
  - Im(L) on vertical axis
- Necessary requirement for stability:
  - (-1,0) is on the left side of the Nyquist plot of the open loop L
- Robustness margins:
  - PM: phase margin
  - GM: gain margin



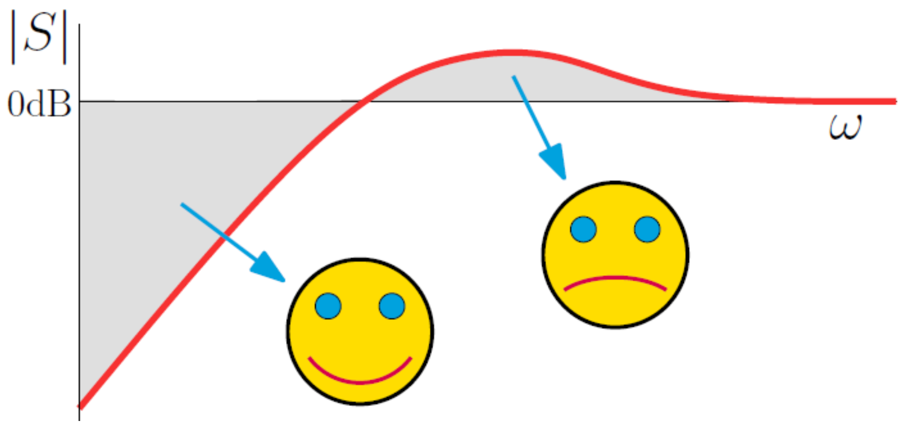
Case study: Nyquist Stability Criterion



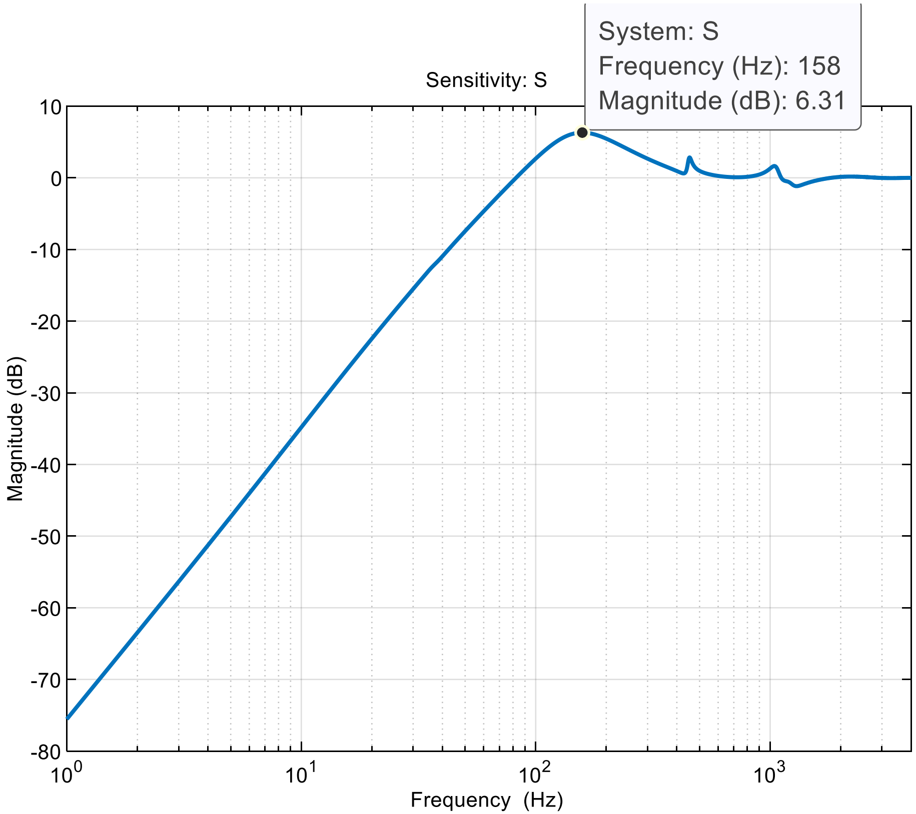
- The Nyquist plot of L:
  - is on the right hand side of the point (-1,0);
  - shows that the closed loop is stable;
  - only slightly enters the 6dB modulus margin region.
- Note:
  - The modulus margin is a measure for robustness
  - The modulus margin corresponds to the peak in the sensitivity
  - Therefore, the sensitivity is expected to have a peak slightly higher than 6dB

Performance assessment using sensitivity function

- The sensitivity function:
  - is a common measure for performance;
  - peak corresponds to modulus margin, typically tuned to be below 6dB for robustness;
  - magnitude corresponds to the amount of disturbance suppression/amplification at a given frequency:
    - $|S| < 0$ dB → Feedback control improves performance;
    - $|S| > 0$ dB → Feedback control deteriorates performance.
- The waterbed effect:
  - suppression of $|S|$ at given frequency results in amplification elsewhere;
  - is a fundamental limitation of linear control.



Case study: sensitivity function

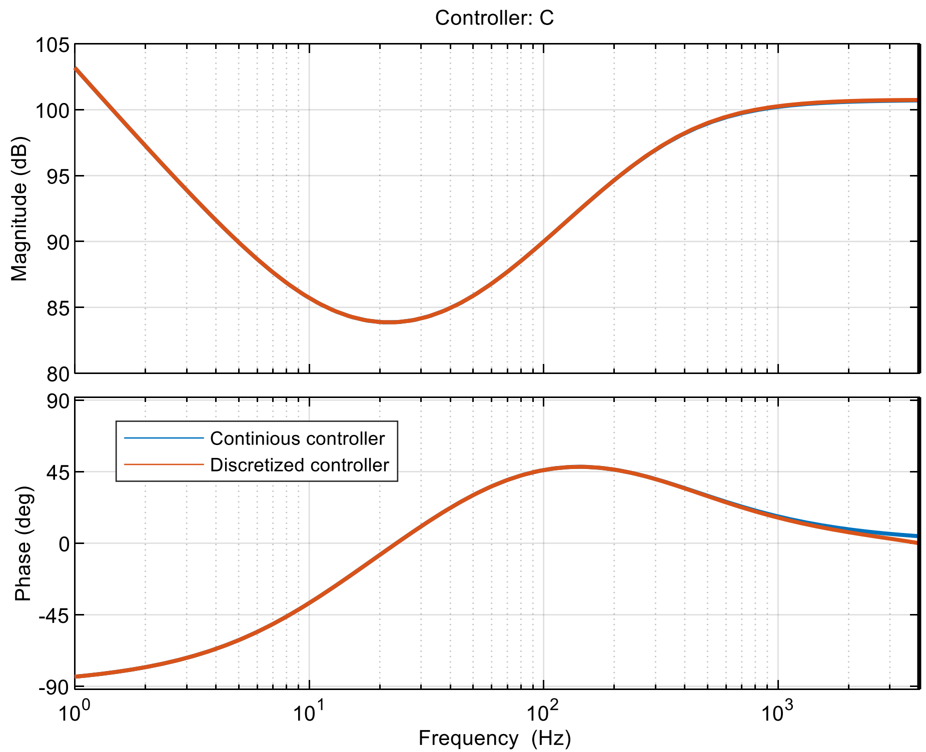


- As expected from the Nyquist plot, the modulus margin is slightly higher than 6 dB
- Up to 82 Hz, the feedback controller improves the performance of the system
- Note:
  - Reference profiles used by ASMPT typically have their dominant energy content in the low-frequency range

Case study: discretization of feedback controller

- Our machines run on a fixed sampling rate
- Therefore, the feedback controller needs to be discretized before implementation on the machine

- Tustin-discretization is a common method to convert a system from the continuous to the discrete time domain
- Discretized and continuous feedback controllers have similar Bode characteristics → discretization successful



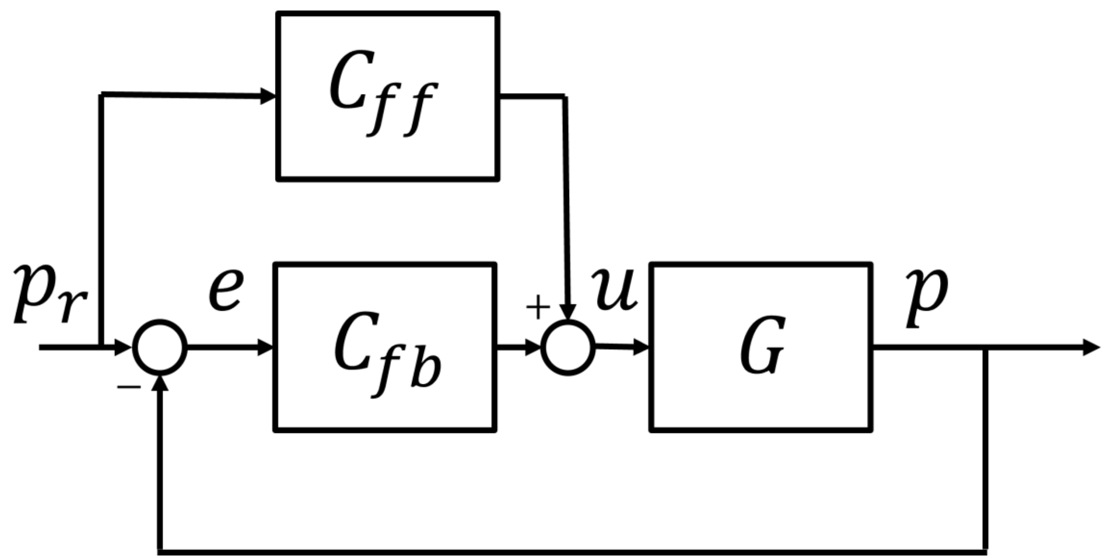
COFFEE BREAK

FEEDFORWARD CONTROL

Motion control system (with feedforward control)

- p_r: reference position
- p: encoder position
- e: error
- u: motor input
- for simplicity, the disturbances are ignored here.

- G: plant
- C_{fb}: feedback controller
- C_{ff}: feedforward controller



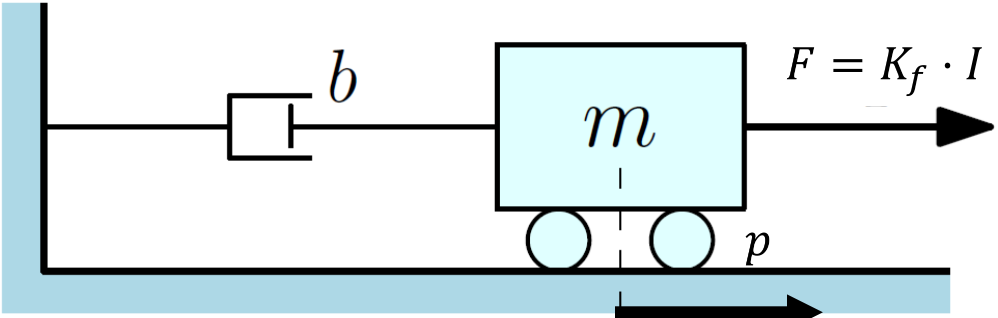
Why feedforward control?

- Feedback reacts to an already existing error and is therefore always lacking behind
- Feedforward uses knowledge about the motion profile and the plant dynamics to deliver the desired motor input before the error can occur

- In principle, if the machine dynamics are exactly known, no feedback is needed. However, in practice:
  - disturbances are present;
  - the machine dynamics are not exactly known.
  - Therefore, combining feedback and feedforward is the way to go.

Feedforward: simple example

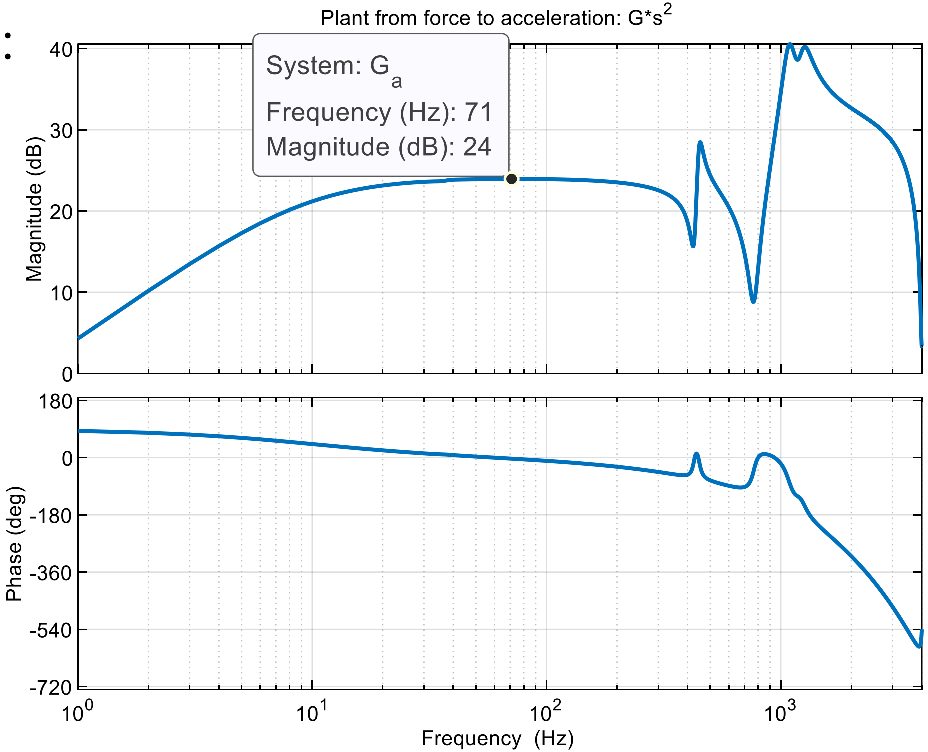
- We want to control the following system:
  - $G(s) = \frac{p(s)}{I(s)} = \frac{K_f \cdot p(s)}{F(s)} = \frac{K_f}{ms^2+bs}$
  - with, position p, force F, current I, mass m, viscous friction b, force constant K_f, and Laplace variable s
- The optimal feedforward controller is given by:
  - $C_{ff}(s) = \left(G(s)\right)^{-1} = \frac{I(s)}{p(s)} = \frac{m}{K_f}s^2 + \frac{b}{K_f}s = K_a s^2 + K_v s$
  - $I(s) = (K_a s^2 + K_v s)p(s)$
  - Conversion to time domain: $\mathrm{I}(t) = K_a \ddot{\mathrm{p}}(t) + K_v \dot{p}(t)$
  - Therefore, an acceleration and velocity feedforward need to be used for this system, with feedforward parameters K_a and K_v.
  - For many motion systems within ASMPT, a feedforward consisting of an acceleration and velocity element are capable to capture the desired current to follow a given motion profile with >90% accuracy.



How to obtain the feedforward parameters? (K_a)

- An initial guess of the acceleration feedforward parameter K_a can be directly estimated from the plant FRF:

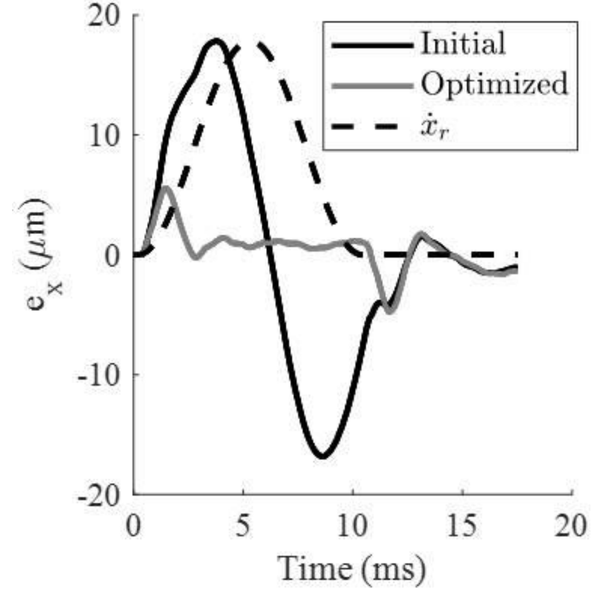
  1. Measure the FRF from current I to position p. i.e., $G(s) = \frac{p(s)}{I(s)}$
  2. Take the 2nd derivative of this FRF: $G(s) \cdot s^2 = \frac{p(s)}{I(s)} \cdot s^2 = \frac{\ddot{p}(s)}{I(s)}$
  3. Obtain the magnitude of the horizontal part of the FRF for the estimation of the acceleration feedforward parameter: $K_a = \frac{1}{db2mag(24)} = 0.0631\ [\mathrm{As^2/m}]$



How to obtain the feedforward parameters? (K_v)

- Obtaining an initial guess of the velocity feedforward parameter K_v is much more difficult in practice

- Starting from the initial estimate of K_a, the feedforward parameters K_a and K_v can be further finetuned with the machine in the loop until the servo errors are minimized:
  - This can be done manually by trial & error, but more advanced automated methods do exist



CONCLUSIONS

Conclusions

- Feedback and feedforward control should work together in harmony.
  - Feedforward control: to deal with the machine dynamics that are known prior to the movement
  - Feedback control: to deal with the remaining unknown machine dynamics & external disturbances that always exist in practice
- Loop shaping is one of the easiest methods to tune a feedback controller. General rules of thumb result in a satisfactory controller in many situations
- Feedforward controller parameters can be partially derived based on machine data, but some manual trial & error will be required for fine-tuning in the explained method

Next steps

- Not satisfied with the obtained performance yet?

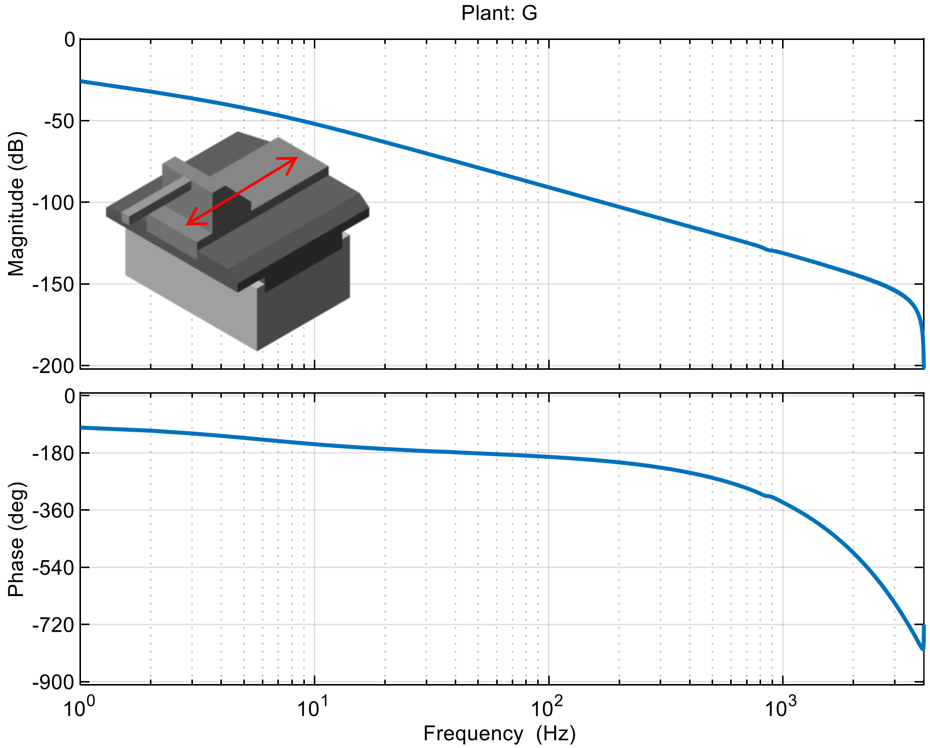
- The Center of Competency can help to further improve:
  - Feedback control → by means of the FeedBack Autotuner (FBA)
  - Feedforward control → by means of
    - Surrogate modelling optimization
    - Iterative learning control (ILC) with basis functions

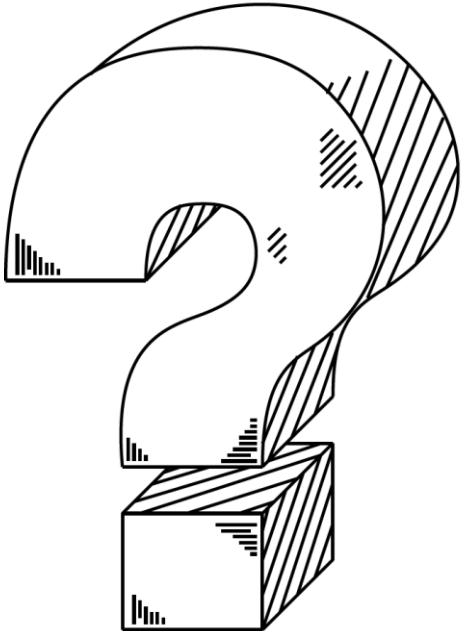
- Feel free to contact us!

SELF-STUDY ASSIGNMENT

Self-study assignment: Y-stage of AB383 Simscape model

- In this training, the X-stage of the AB383 Simscape model has been used as an example to design a feedback and feedforward controller.
- Now, try for the Y-stage:
  1. Design a feedback controller:
     - using loop-shaping,
     - with a bandwidth as high as possible,
     - with a modulus margin of less than 6 dB.
  2. Design a feedforward controller:
     - by obtaining the acceleration parameter using a frequency domain analysis.





QUESTIONS

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