FRTN10 Multivariable Control, Lecture 5

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Course Outline

L1-L5 Specifications, models and loop-shaping by hand
1. Introduction and system representations
2. Stability and robustness
3. Specifications and disturbance models
4. Control synthesis in frequency domain
5. Case study

L6-L8 Limitations on achievable performance

L9-L11 Controller optimization: Analytic approach

L12-L14 Controller optimization: Numerical approach

Lecture 5: Case Study

- Review of concepts from Lecture 4
  - Frequency-domain specifications
  - Loop shaping
- Case Study: Control of DVD reader
  - Focus control
  - Radial control
  - Demo
- Review of cascade and midranging control

Frequency-domain specifications

Would like S and T to be small at all frequencies

Impossible! $S + T = 1$ and other fundamental limitations

Compromise: Make S small for low frequencies and T small for high frequencies

Specify “forbidden” areas for S and T using W_S and W_T:

- $|S(i\omega)| \leq |W_S^{-1}(i\omega)|$
- $|T(i\omega)| \leq |W_T^{-1}(i\omega)|$

Loop shaping

Controller synthesis via loop shaping: Shape the **open loop gain** $L = CP$ so that

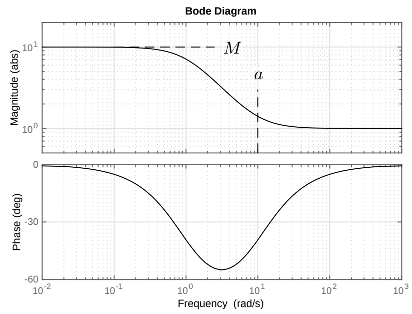
- $|L| > |W_S|$ for low frequencies
- $|L| < |W_T^{-1}|$ for high frequencies
- good stability margins (M_s, φ_m, A_m) are achieved

The controller C is typically composed of several factors:

- gain
- lag filters
- lead filters
- other filters (e.g., notch filter)

Lag Filter

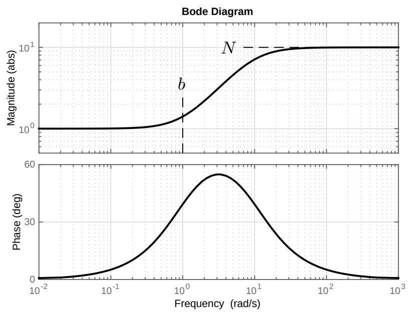
$$G_{lag}(s) = \frac{s+a}{s+a/M}, \quad M > 1$$



Special case: $M = \infty \Rightarrow$ integrator

Lead Filter

$$G_{lead}(s) = N\frac{s+b}{s+bN}, \quad N > 1$$



Maximum phase advance for different N given in Collection of Formulae

Lecture 5: Case Study

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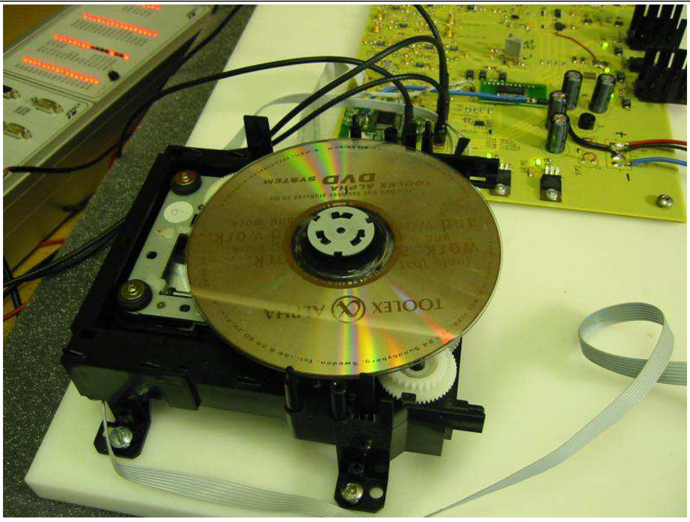
Case Study: Control of DVD reader

- The DVD reader process
- Problem formulation
- Modeling
- Specifications
- Focus control loop shaping
- Radial control (track following)
- Experimental verification

Based on work by Bo Lincoln



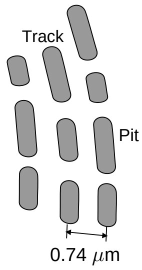
The DVD reader tracking problem

Scaled version of the control task in a DVD player:

- Imagine that you are traveling at half the speed of light, along a line from which you may only deviate 1 m
- The line is not straight but oscillates up to 4.5 km sideways 23 times per second

Good luck!

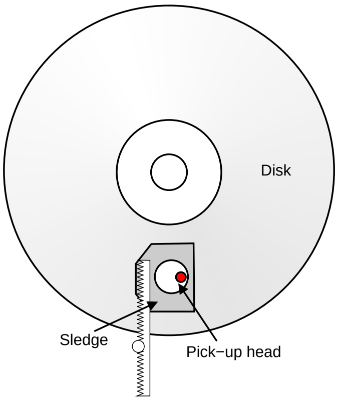
The DVD reader tracking problem

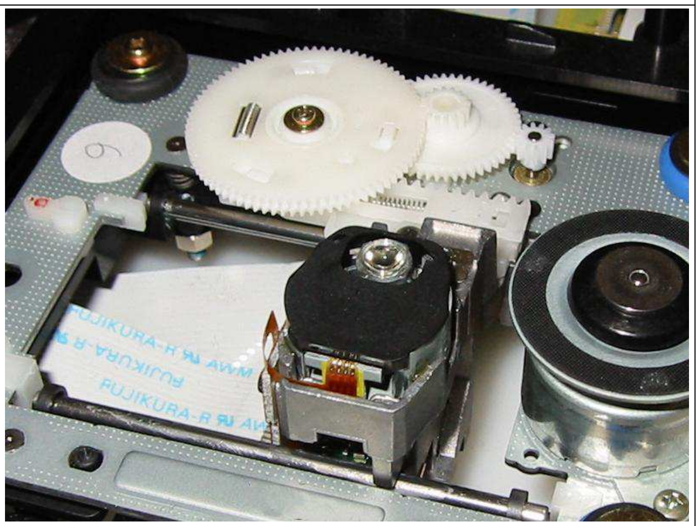


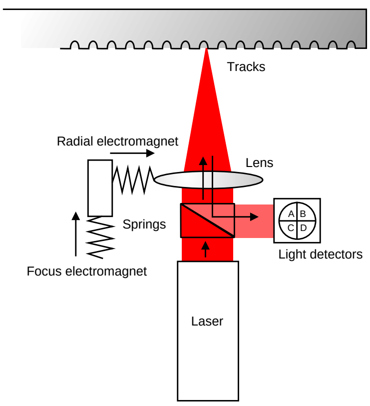
- 3.5 m/s speed along track
- 0.022 μm tracking tolerance
- 100 μm deviations at 23 Hz due to asymmetric discs

DVD Digital Versatile Disc, 4.7 Gbytes
CD Compact Disc, 650 Mbytes

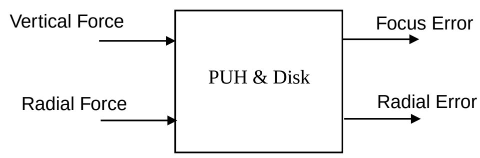
The DVD Pick-Up Head



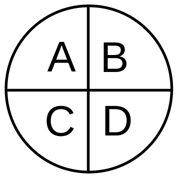




Input-output diagram for DVD control



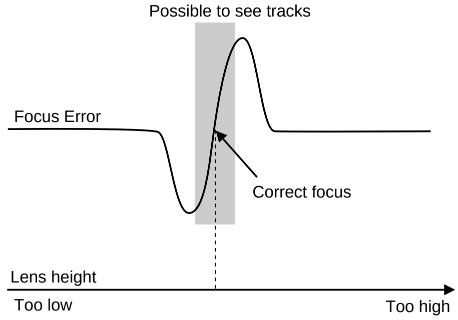
The four photo detectors



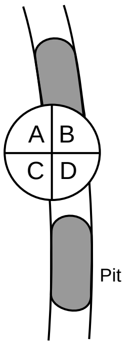
focus error = (A+D) – (B+C)

Note: *There are no other sensors in the pick-up head to help keep the laser in the track.*

Focus error signal



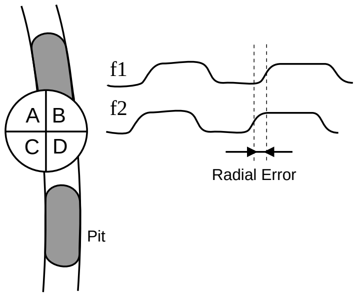
Radial error by push-pull



Look at

$$(A + C) - (B + D)$$

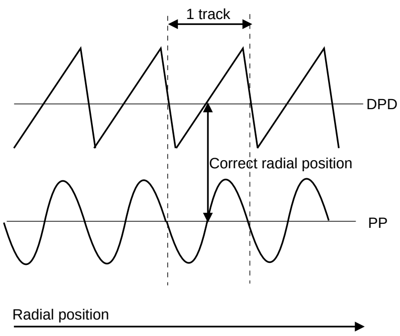
Radial error by phase-difference (DPD)



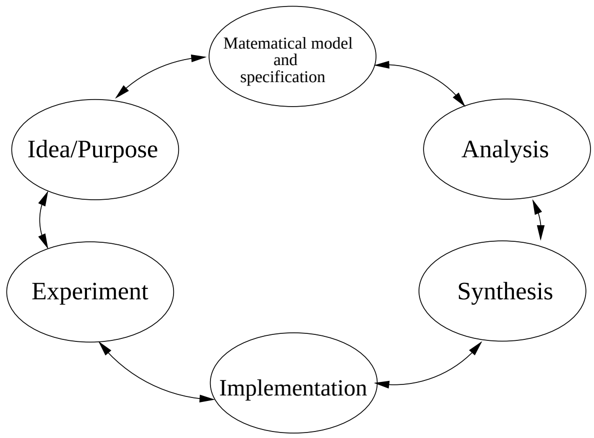
$$f_1 = A + D, \qquad f_2 = B + C$$

Error signal RE created by time difference

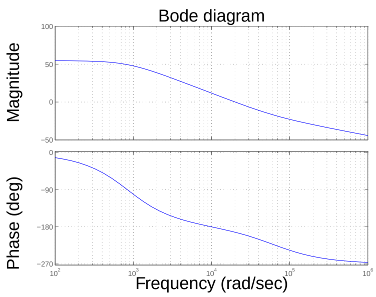
Radial error signals



Note: Larger linear error region if using DPD.

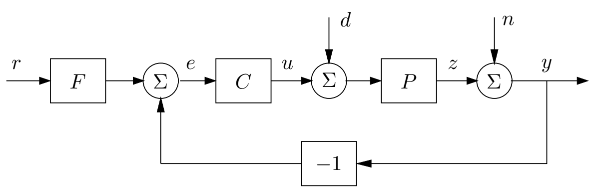


Experimental focus dynamics model



$$P_f(s) = 6092 \frac{63168 - s}{s^2 + 1553s + 718214}$$

What Signals are Relevant for Focus Control?



Specifications

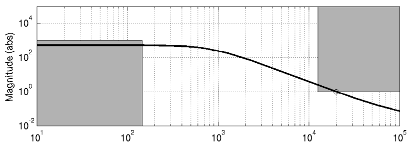
Cancel disturbances due to disc asymmetry

$$|C(i\omega)P_f(i\omega)| \geq 1000 \qquad \text{for } \omega \leq 23.1 \text{ Hz}$$

Reject measurement noise

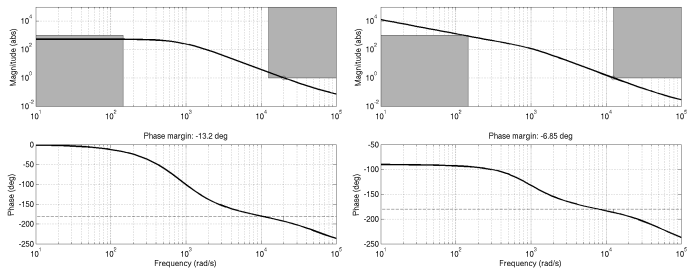
$$|C(i\omega)P_f(i\omega)| \leq 1 \qquad \text{for } \omega > 2 \text{ kHz}$$

(Compare to the bit rate, which is in the order of 1 MHz)



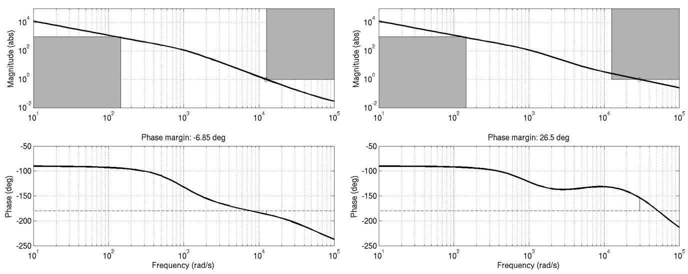
Lag Compensator

Use lag filter to increase the gain below 24 Hz. The break point needs to be well below 2 kHz in order to avoid additional phase lag at the cross-over frequency: $C_1(s) = 0.4\frac{s+600}{s}$



Lead and Lag Compensators

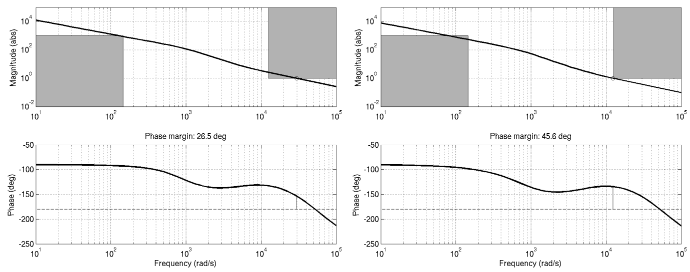
Further compensation is needed for stability. A lead filter to increase the phase near 2 kHz; $C_2(s) = 0.4\frac{s+600}{s}\frac{1+s/5000}{1+s/50000}$.



Adjust the gain

The gain needs to be adjusted at high frequencies.

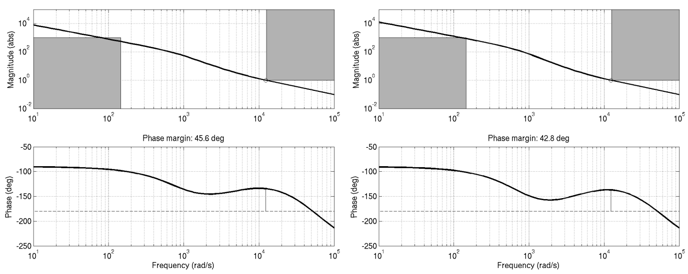
Now the closed loop system is stable with good margins, but the gain at 23.1 Hz is still too low, just 100 instead of 1000;



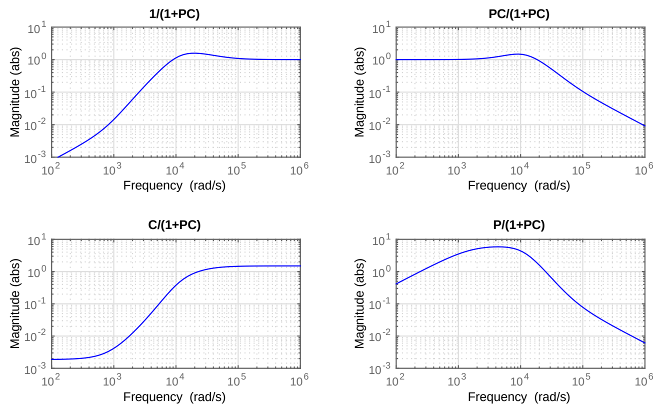
Final controller

The gain at 23.1 Hz can be corrected by modifying the break point of the lag filter to get the final controller
$C(s) = 0.15\frac{s+1600}{s}\frac{1+s/5000}{1+s/50000}$.

Notice that this is in fact a PID controller in serial form,
$C(s) = K'\left(1 + \frac{1}{sT_i'}\right)\frac{1+sT_d'}{1+sT_d'/N'}$



Gang of Four for the Final Controller



Radial control

Make the laser follow the track by moving "sideways"/radially

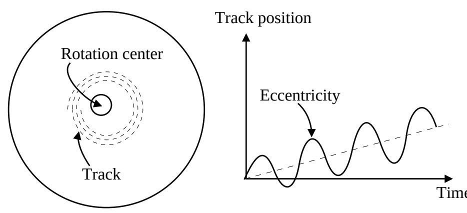
It is essential to solve the Focus control problem first

Tracking via two parallel actuators (midranging):

- Move lens (electromagnet/fast motion)
- Move sledge (slow/large range)

Disturbances:

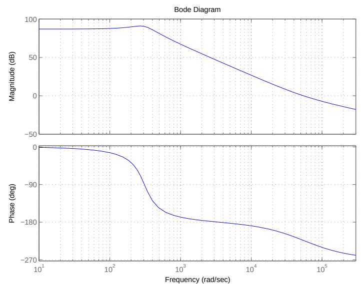
- eccentricity (up to 100 tracks in one rotation)
- physical vibrations of DVD player
- noise, dirt, etc.



The disc is often a bit eccentric (i.e. not rotating around the track center). The resulting track position, which the Pick-Up-Head has to follow, is sinus-like.

Experimental radial dynamics model

An estimated transfer function for the radial servo (from the control signal u to the radial error RE)



System identification made by sinusoidal excitation.

DVD specification (standard ECMA-267)

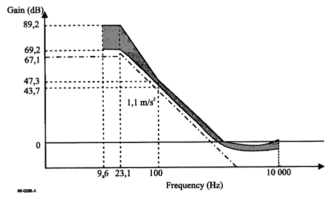


Figure 4 - Reference Servo for Radial Tracking

Bandwidth from 100 Hz to 10 kHz

$|1 + H|$ shall be within 20 % of $|1 + H_s|$.

The crossover frequency $f_0 = \omega_0 / 2\pi$ shall be specified by equation (III), where α_{max} shall be 1,5 times larger than the expected maximum radial acceleration of 1,1 m/s². The tracking error e_{max} shall not exceed 0,022 µm. Thus the crossover frequency f_0 shall be

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3\,\alpha_{max}}{e_{max}}} = \frac{1}{2\pi}\sqrt{\frac{1{,}1 \times 1{,}5 \times 3}{0{,}022 \times 10^{-6}}} = 2{,}4 \text{ kHz} \qquad \text{(III)}$$

The figure on the previous slide is a copy from the DVD specification, standard ECMA-267.

The plot shows the specified $|1 + G_r C_r|$, which is the inverse of the sensitivity function, and the curve corresponds roughly to the *open-loop transfer function.*

In clear text, the specification requires the following:

- A low-frequency (< 23 Hz) gain of 70 dB or more for the open-loop system.
- A cross-over frequency of $\omega_c = 2.4$ kHz $= 15$ krad/s.

Different design choices

There are a number of different design methods to use

Example:

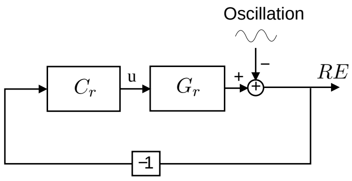
- Loop shaping
- Pole placement
- LQG (Lectures 9–11)
- ...

Problem with output disturbance

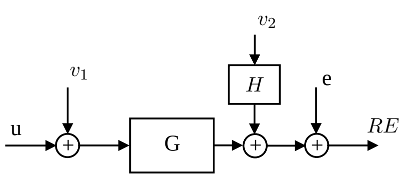
The eccentricity causes problems (about 10-20 Hz and oscillation of up to 100 tracks). Can't be exactly modeled due to uncertainty.

How to proceed?

How to get rid of the oscillation?



A model of how the disk oscillation affects the system. For example, if the oscillation offset at some point in time is +6.2 tracks, the DVD radial servo has to be at +6.2 tracks too to have zero RE.



Noise model: There is both white process noise v_1, and a track-offset which is modeled as the white noise v_2 through a filter H.

When designing a state estimator, we can give the Kalman filter a "hint" of what to expect, by modeling the eccentricity as white noise through a filter H as shown in the figure above. The filter H should have a high gain in the frequency range where the oscillation acts.

From lecture 3...

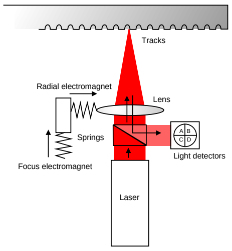
If w_1 and w_2 are colored noise then re-write w_1 and w_2 as output signals from linear systems with *white noise inputs* v_1 and v_2 .

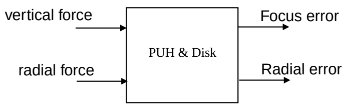
$$w_1 = G_1(p)v_1, \qquad w_2 = G_2(p)v_2$$

Make state-space realizations of G_1 and G_2 and extend the system description with these states

$$\dot{\overline{x}}(t) = \overline{A}\overline{x}(t) + \overline{B}\overline{u}(t) + \overline{N}v_1(t)$$
$$z(t) = \overline{M}\overline{x}(t) + D_z u(t)$$
$$y(t) = \overline{C}\overline{x}(t) + D_y u(t) + v_2(t)$$

Experiment





DEMO

References

See also

- Lecture notes L5 on web page
- `http://libhub.sempertool.dk/`
  (available from `lu.se`-domain)
  "Sensing and Control in Optical Drives How to Read Data from a Clear Disc" by Amir H. Chaghajerdi, June 2008, IEEE Control Systems Magazine, pp. 23-29

Lecture 5: Case Study

- Review of concepts from Lecture 4
  - Frequency-domain specifications
  - Loop shaping
- Case Study: Control of DVD reader
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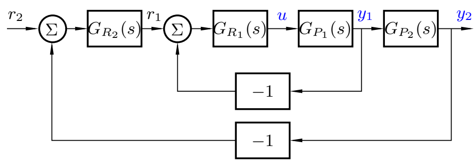
Cascade control

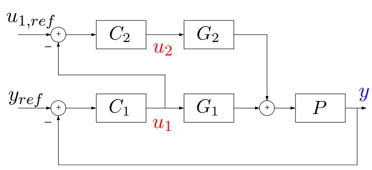
For systems with one control signal and many outputs:



- $G_{R_1}(s)$ controls the subsystem $G_{P_1}(s)$ $(\Rightarrow G_{y_1 r_1}(s) \approx 1)$
- $G_{R_2}(s)$ controls the subsystem $G_{P_2}(s)$

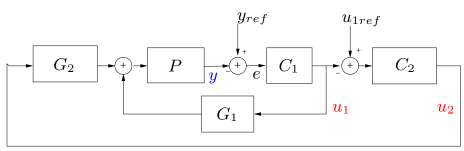
Mid-ranging Control

- Mid-ranging control structure is used for processes with two inputs and only one output to control.
- A classical application is valve position control
- Fast process input u_1 (Example: fast but small ranged valve)
- Slow process input u_2 (Example: slow but but large ranged valve)



Q: What should $u_{1,ref}$ be?
How does the midranging controller work?

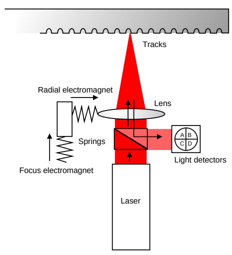
Mid-ranging control - a dual to cascade control

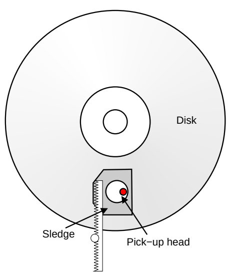


- First tune the fast inner loop, then the slower outer loop
- Controllers have separate time scales to avoid interaction

Mid-ranging cont'd

Example: Radial control of pick-up-head of DVD player





The pick-up-head has two electromagnets for fast positioning of the lens (left). Larger radial movements are taken care of by the sledge (right).

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L6-L8 Limitations on achievable performance
  6. Controllability, observability, multivariable zeros
  7. Fundamental limitations
  8. Multivariable and decentralized control
L9-L11 Controller optimization: Analytic approach
L12-L14 Controller optimization: Numerical approach