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

Previous lecture

Lecture 4:

- Specifications in frequency domain
- Loop shaping design

The synthesis methods will be used in both todays case study and in Lab 1.

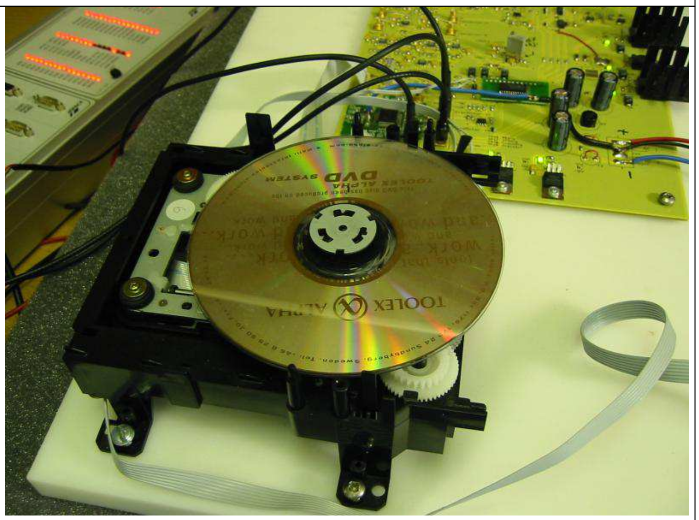
Don't forget to sign up for lab 1 on home page.

Lecture 5 — Control of DVD reader

- Focus control
- Radial control (Track following)

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

based on work by Bo Lincoln



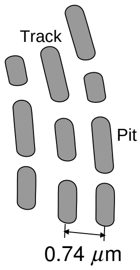
The DVD-reader tracking problem

Scaled version of the control task in a DVD player

- 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!

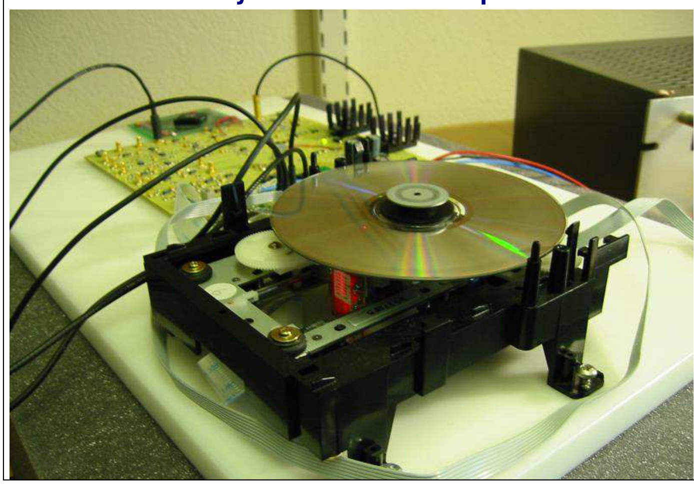
The DVD-reader tracking problem

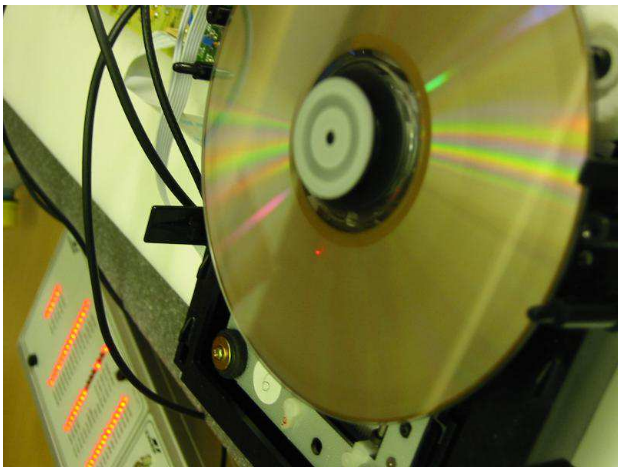


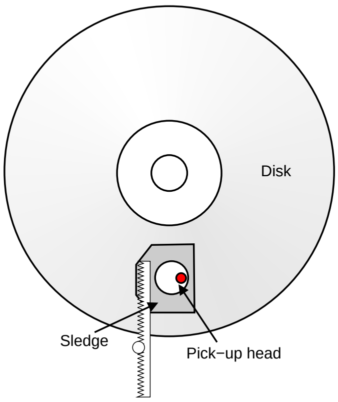
- 3.5 m/s speed along track
- 0.022 μm tracking tolerance
- 100 μm deviations at 23 Hz due to assymetric discs

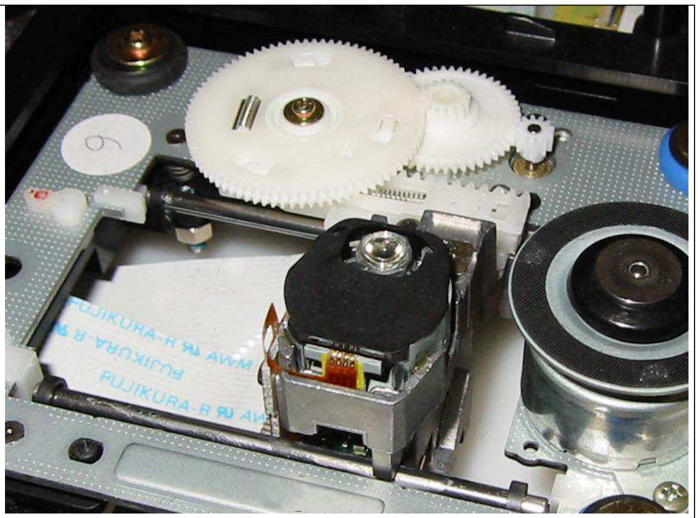
DVD Digital Versatile Disc, 4.7 Gbytes
CD Compact Disc, 650 Mbytes

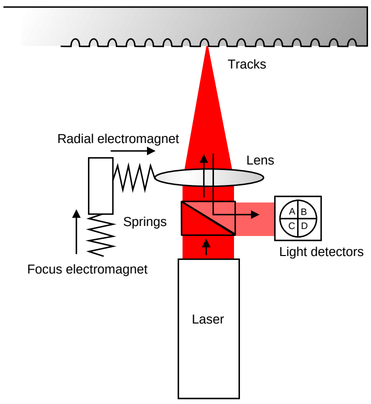
Can you see the laser spot?



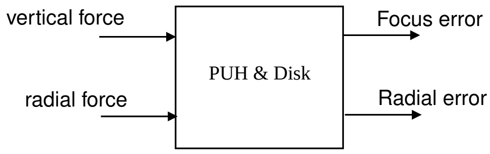




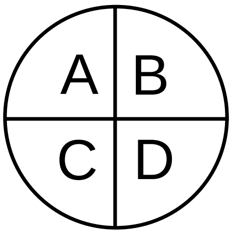




Input-output diagram for DVD control



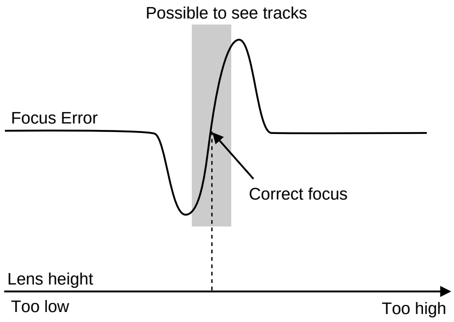
The four photo detectors



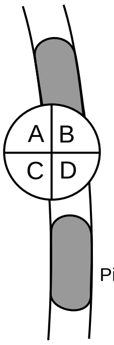
focus error = (A+D) – (B+C)

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

Focus error signal



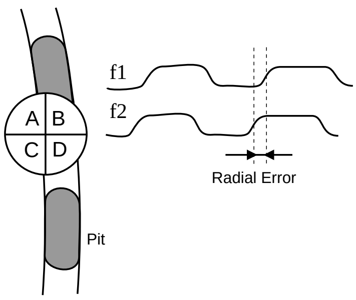
Radial error by push-pull



Look at

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

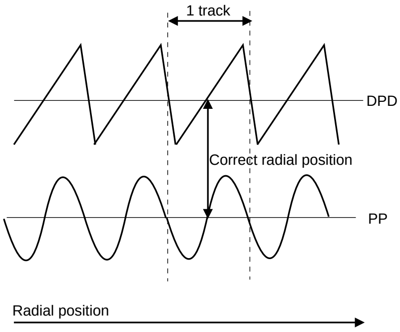
Radial error by phase-difference (DPD)



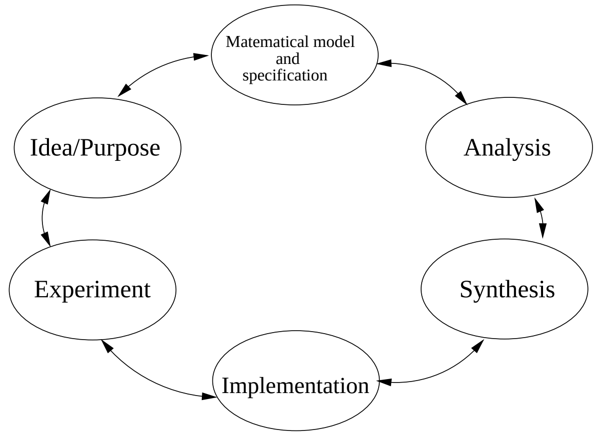
$$f_1 = A + D, \qquad f_2 = B + C$$

Error signal RE created be time difference

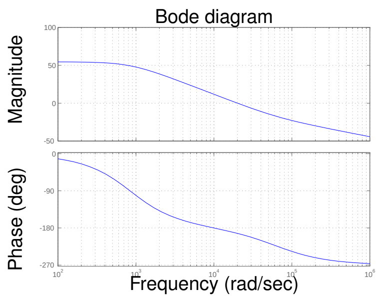
Radial error signals



Note: Larger linear error region if using DPD.

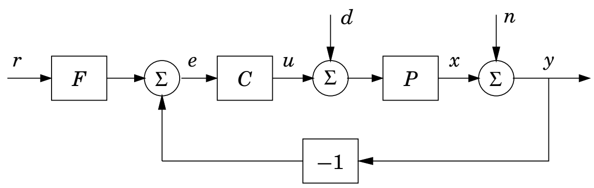


Experimental frequency response model



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

What Signals are Relevant for Focus Control?



Specifications

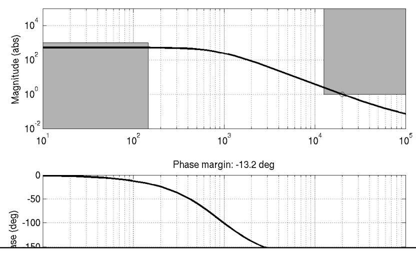
Cancel disturbances due to disc assymmetry

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

Reject measurement noise

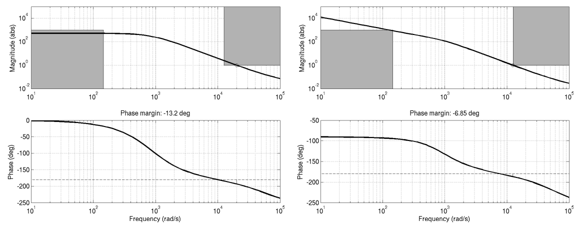
$$|C(i\omega)P_f(i\omega)| \leq 1 \qquad \text{for } \omega > 2 \text{ kHz}$$

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



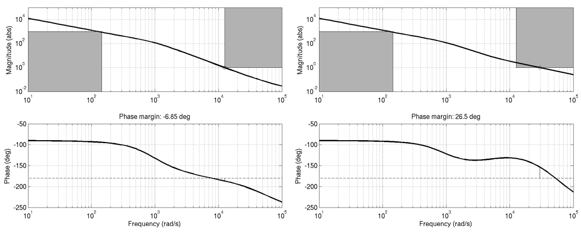
First Order Lag Compensator

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 cut-off frequency: $C_1(s) = 0.4\frac{s+600}{s}$



Lead and Lag Compensators

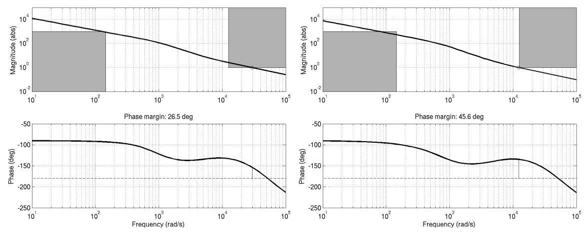
Further compensation is needed for stability. A lead filter to increase the phase near 2 kHz; $C_2(s) = 0.4\frac{s+600}{s}\frac{1+s/5000}{1+s/50000}$.



Adjust gain

The gain needs to be adjusted at high frequencies.

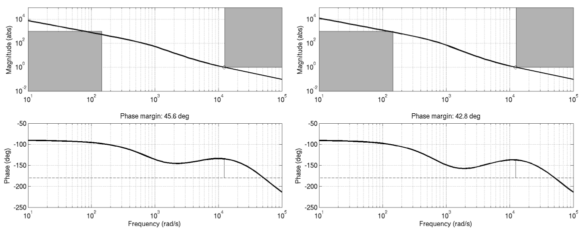
Now the closed loop system is stable with good margins, but the gain at 23.1 Hz is still too low, just 100 instead of 1000;



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 very similar to a PID controller of the form
$C(s) = K\left(\frac{1}{sT_i} + \frac{sT_d}{1+sT_d/N}\right)$.



Radial control

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

The Focus control problem is essential to solve first

Tracking via

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

Disturbances

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

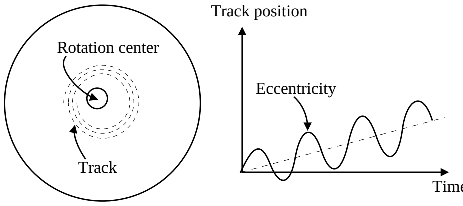
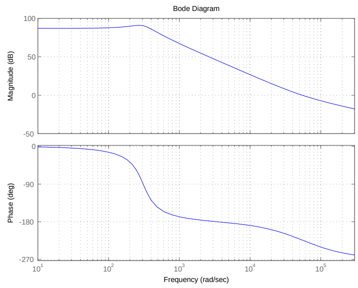


Figure : The disc is often a bit eccentric (i.e. not rotating around the track center). The resulting track position, which the Pick-Up-Head has to follow, is a sinus-like.

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)

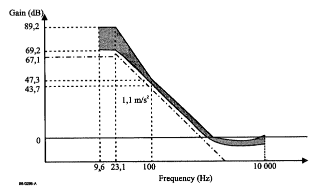


Figure 4 - Reference Servo for Radial Tracking

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/s^2. 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 plot on previous slide is a copy from the DVD specification, standard ECMA-267.

The plot shows the specified $|1 + G_{\text{radial}} \cdot C_{\text{radial}}|$, 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 cut-off 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 ("State feedback" in combination with Kalman filter)
- ...

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 oscillation?

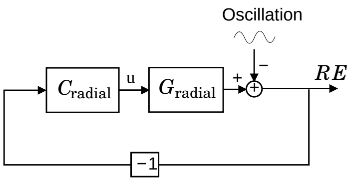


Figure : A model of how the disk oscillation affects the system. For example, if the oscillation offset at some point in time is +6.2 tracks, the DVD radial servo has to be at +6.2 tracks too to have zero RE.

From lecture 3...

If w_1 and w_2 is 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 a state space realization of G_1 and G_2 and extend the system description with these states

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

where the *extended state* $\overline{x}$ consists of the state x and the states from the state-space realizations of G_1 and G_2.

$\overline{A}$ is the corresponding system matrix for the extended system etc.

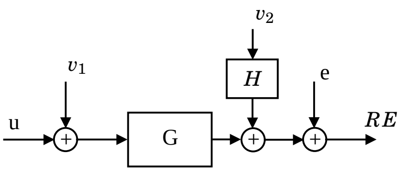
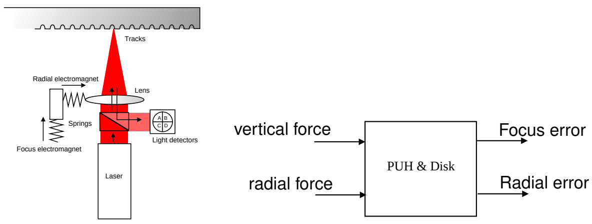


Figure : Noise model: There is both white process noise v_1, and a track-offset which is modeled as the white noise v_2 through a filter H.

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.



Experiment

DEMO

Summary

- Problem formulation
- Modeling
- Specifications
- Focus loop shaping
- Track following
  - specs
  - disturbance modelling
  - LQG-design will follow in Lectures 9-11
- Experimental verification

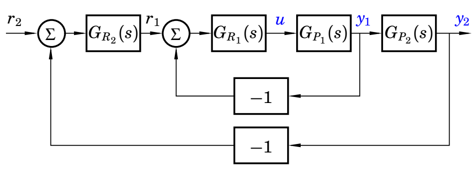
References

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

Cascade control

For systems with one control signal and many outputs:

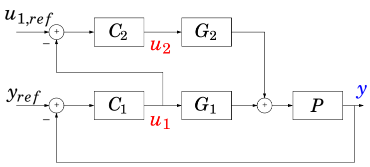


- $G_{R_1}(s)$ controls the subsystem $G_{P_1}(s)$ $(\Rightarrow G_{y_1 r_1}(s) \approx 1)$
- $G_{R_2}(s)$ controls the subsystem $G_{P_2}(s)$

Often used in motion control, e.g., robotics, with cascaded velocity and position controllers, BUT should have velocity reference feedforward!!

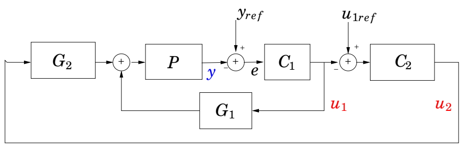
Mid-ranging Control

- 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?

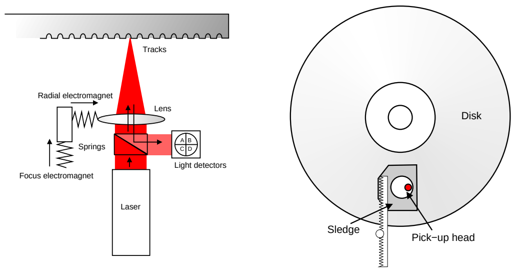
Mid-ranging control - a dual to cascade control



- 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 pich-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).

Next lecture

Lecture 6

- Controllability and observability
- Singular values
- Multivariable zeros

L1-L5 Specifications, models and loop-shaping by hand
L6-L8 Limitations on achievable performance