FRTN10 Multivariable Control, Lecture 5

Automatic Control LTH, 2016

Course Outline

L1-L5 Specifications, models and loop-shaping by hand
1. Introduction
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 – Outline

1. Case Study: Control of a DVD reader
   - Focus control
   - Radial control
2. Review of cascade and midranging control

Loop shaping

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

- $[L] > |W_S|$ for low frequencies (disturbance rejection)
- $|L| < |W_T^{-1}|$ for high frequencies (robustness, att. of meas. noise)
- good stability margins (φ_m, A_m, M_s) are achieved

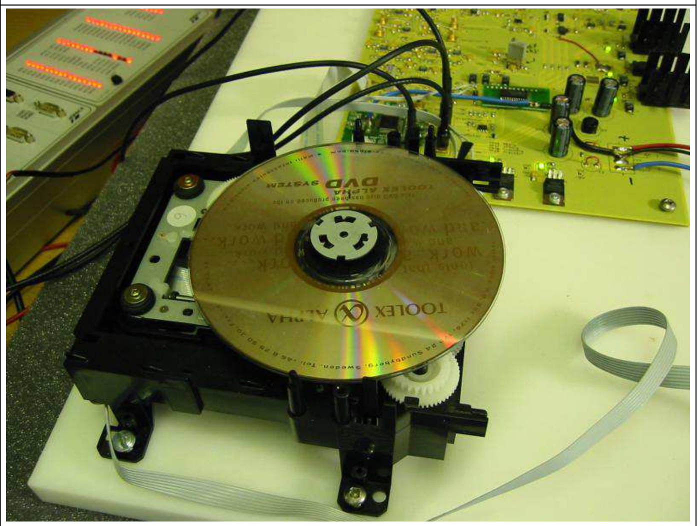
The controller C is typically composed of several factors:

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

Case Study: Control of a DVD reader

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

Based on work by Bo Lincoln



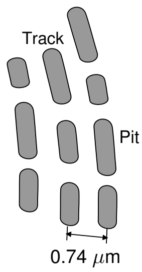
The DVD reader tracking problem

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 25 times per second

Good luck!

The DVD reader tracking problem



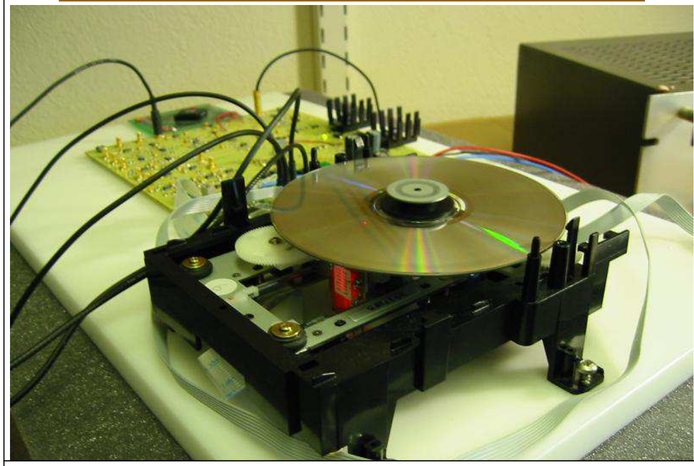
- 3.5 m/s speed along track
- 0.022 μm tracking tolerance
- 100 μm deviations at 10–25 Hz due to asymmetric discs

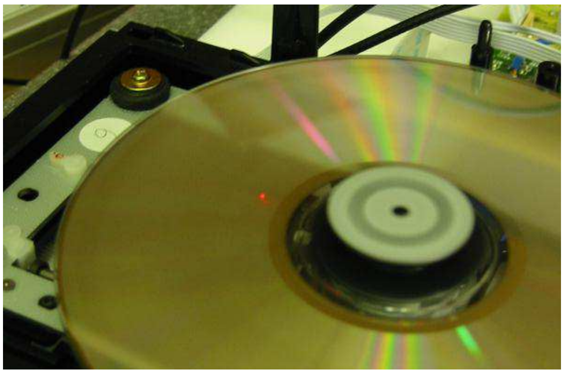
DVD Digital Versatile Disc, 4.7–8.5 GB

CD Compact Disc, 650–800 MB

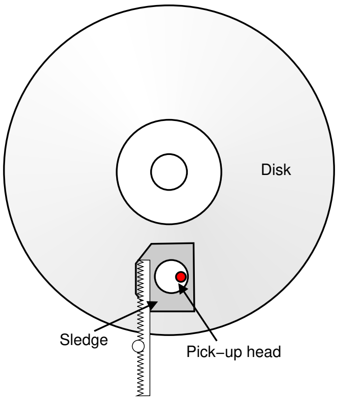
Blu-ray 25–400 GB

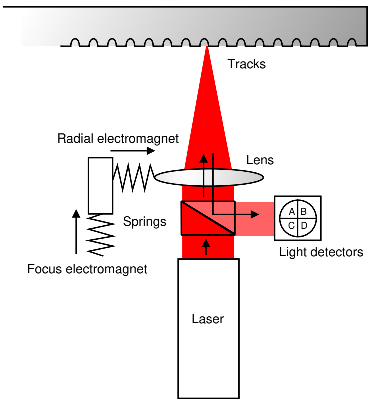
Can you see the laser spot?



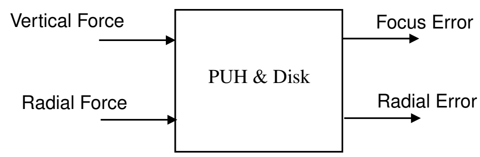


The DVD Pick-Up Head

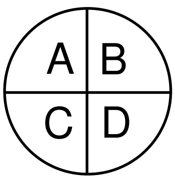




Input-output diagram for DVD control



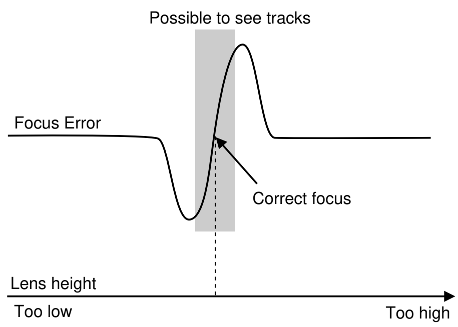
The four photo detectors



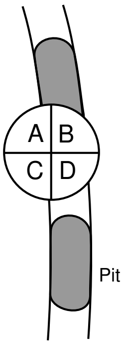
focus error = (A+D) – (B+C)

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

Focus error signal



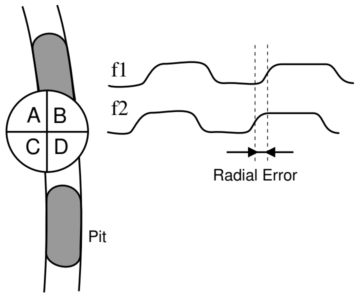
Radial error by push-pull



Look at

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

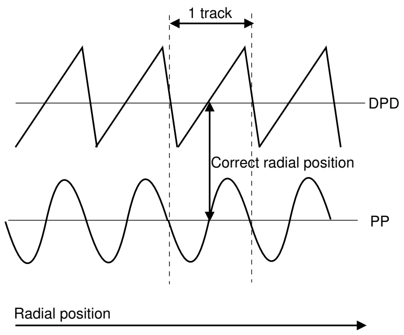
Radial error by phase difference



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

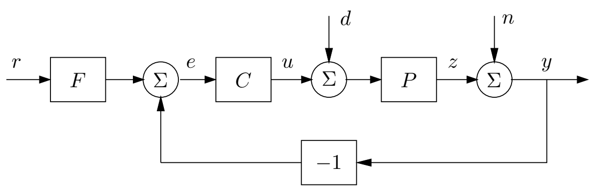
Error signal RE created by time difference

Radial error signals



Note: Larger linear error region if using phase difference.

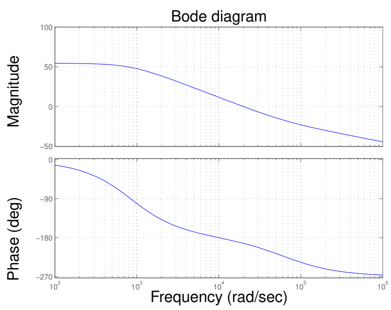
Focus control design



- What blocks and signals are relevant for focus control?
- What disturbances are there?

Focus process model

Model obtained using system identification:



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

Specifications

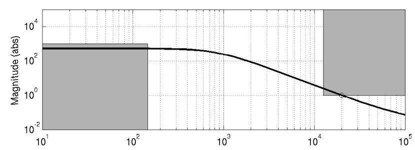
Cancel disturbances due to disc asymmetry

$$|P(i\omega)C(i\omega)| \geq 1000 \qquad \text{for } \omega \leq 25 \text{ Hz}$$

Robustness towards model errors, rejection of meas. noise

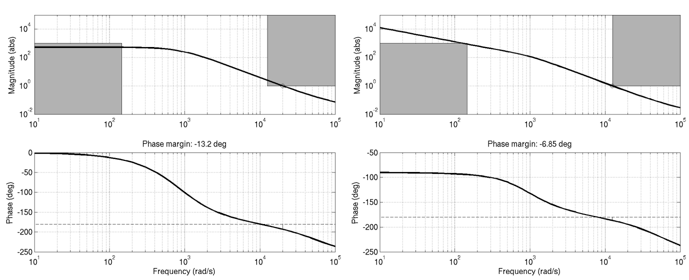
$$|P(i\omega)C(i\omega)| \leq 1 \qquad \text{for } \omega > 2 \text{ kHz}$$

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



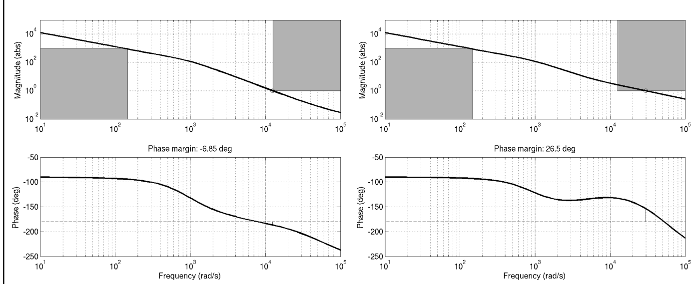
Lag Compensator

Use lag filter to increase the gain below 25 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

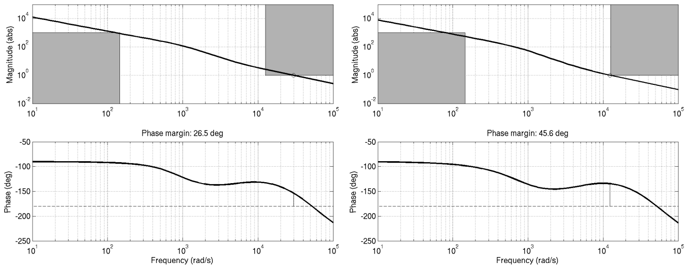
Further compensation is needed for stability. A lead filter to increase the phase near 2 kHz; $C_2(s) = 0.4\frac{s+600}{s}\frac{1+s/5000}{1+s/50000}$.



Adjust the gain

The gain needs to be adjusted at high frequencies.

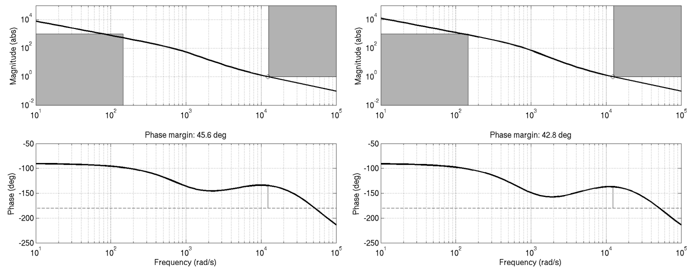
Now the closed loop system is stable with good margins, but the gain at 25 Hz is still too low, just 100 instead of 1000;



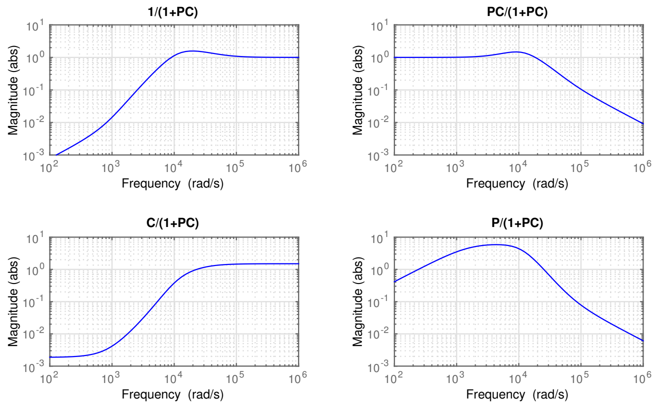
Final controller

The gain at 25 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

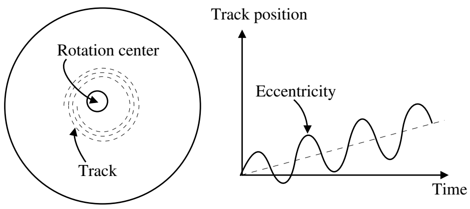
It is essential to solve the Focus control problem first

Tracking via two parallel actuators (midranging):

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

Disturbances:

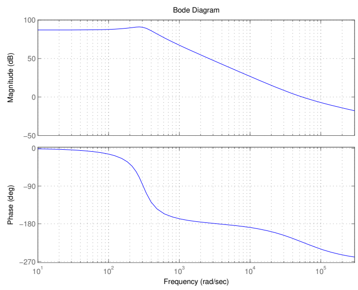
- eccentricity (up to 100 tracks in one rotation)
- physical vibrations of DVD player
- noise, dirt, etc.



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)

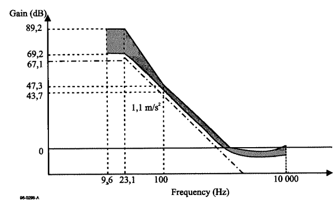


Figure 4 - Reference Servo for Radial Tracking

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/s^2. The tracking error e_{max} shall not exceed 0,022 µm. Thus the crossover frequency f_0 shall be

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3\,\alpha_{max}}{e_{max}}} = \frac{1}{2\pi}\sqrt{\frac{1{,}1\times1{,}5\times3}{0{,}022\times10^{-6}}} = 2{,}4 \text{ kHz} \qquad \text{(III)}$$

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

The plot shows the specified $|1+PC|$, 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 (< 25 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:

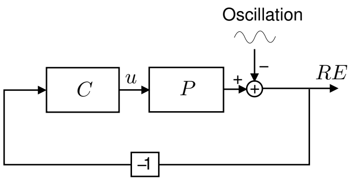
- Loop shaping
- Pole placement
- LQG (Lectures 9–11)
- ...

Problem with output disturbance

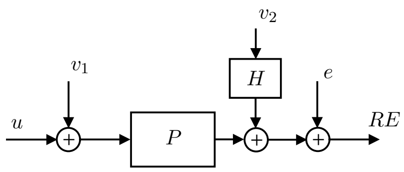
The eccentricity causes problems (about 10–25 Hz and oscillation of up to 100 tracks). Can't be exactly modeled due to uncertainty.

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

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

References

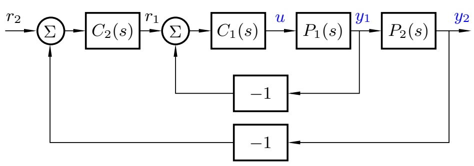
See also

- Lecture notes on course web page
- "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,

`http://www.ieeecss.org/CSM/library/2008/june08/11-June08ApplicationsOfControl.pdf`

Cascade control

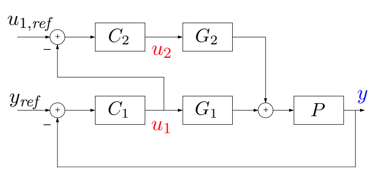
For systems with one control signal and two (or more) outputs:



- $C_1(s)$ controls the subsystem $P_1(s)$
  - Fast inner loop, $G_{y_1 r_1}(s) \approx 1$
- $C_2(s)$ controls the subsystem $P_2(s)$
  - Slow outer loop

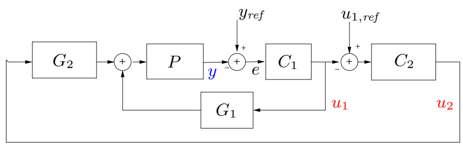
Midranging Control

- Midranging is used for processes with two inputs and one output
- Classical application: valve position control
- Fast process input u_1 (Example: fast but small-range valve)
- Slow process input u_2 (Example: slow but but large-range valve)



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

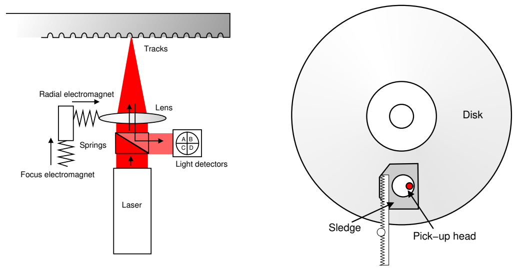
Midranging control – a dual to cascade control



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

Midranging 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).