Course Outline

Previous lecture

Lecture 4:

- Specifications in frequency domain
- Loop shaping design

Topic left for today:

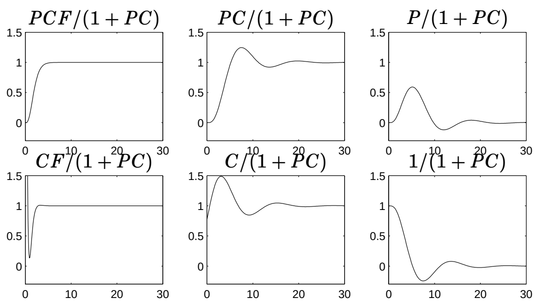
- Feed-forward design

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.

Example: Step Responses

PI control $k = 0.775$, $T_i = 2.05$ of $P(s) = (s+1)^{-4}$



Equivalently

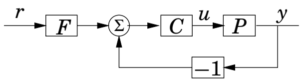
$$F(s) \approx \frac{1+P(s)C(s)}{P(s)C(s)}$$

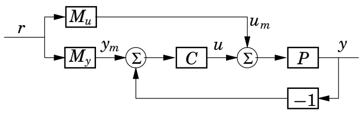
Exact equality is generally impossible because of pole excess in P.

The simplest and most common approximation is to use a constant gain

$$F = \frac{1+P(0)C(0)}{P(0)C(0)}$$

Feedforward design





The reference signal r specifies the desired value of y.

Ideally

$$\frac{P(s)C(s)}{1+P(s)C(s)}F(s) \approx 1$$

A more advanced option is

$$F(s) = \frac{1+P(s)C(s)}{P(s)C(s)(sT+1)^d}$$

for some suitable time constant T and d large enough to make F proper and implementable.

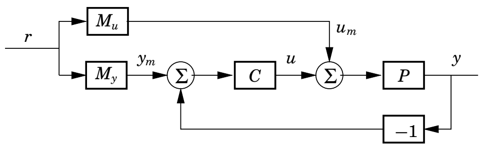
Example

$$P(s) = \frac{1}{(s+1)^4} \qquad F(s) = \frac{1+P(s)C(s)}{P(s)C(s)(sT+1)^d}$$

The closed loop transfer function from r to u then becomes

$$\frac{C(s)}{1+P(s)C(s)}F(s) = \frac{(s+1)^4}{(sT+1)^4}$$

which has low-fq gain 1, but gain $1/T^4$ for $\omega \longrightarrow \infty$.



Notice that M_u and M_y can be viewed as generators of the desired output y_m and the inputs u_m which corresponds to y_m.

Design of Feedforward revisited

The transfer function from r to $e = y_m - y$ is $(M_y - PM_u)S$

Ideally, M_u should satisfy $M_u = M_y/P$. This condition does not depend on C!

Since $M_u = M_y/P$ should be stable, causal and not include derivatives we find that

- Unstable process zeros must be zeros of M_y
- Time delays of the process must be time delays of M_y
- The pole excess of M_y must be greater than the pole excess of P

Take process limitations into account!

Example of Feedforward Design revisited

If

$$P(s) = \frac{1}{(s+1)^4} \qquad M_y(s) = \frac{1}{(sT+1)^4}$$

then

$$M_u(s) = \frac{M_y(s)}{P(s)} = \frac{(s+1)^4}{(sT+1)^4} \qquad \frac{M_u(\infty)}{M_u(0)} = \frac{1}{T^4}$$

Fast response (T small) requires high gain of M_u.

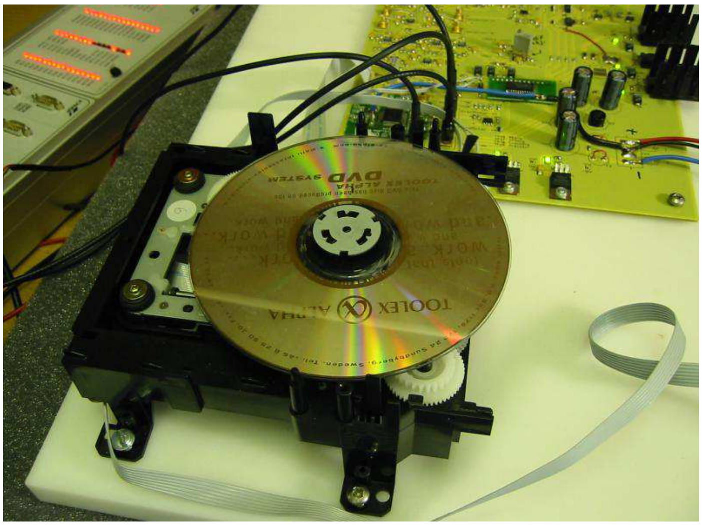
Bounds on the control signal limit how fast response we can obtain.

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



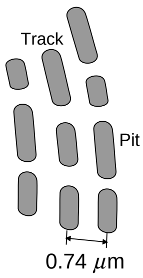
The DVD-reader tracking problem

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!

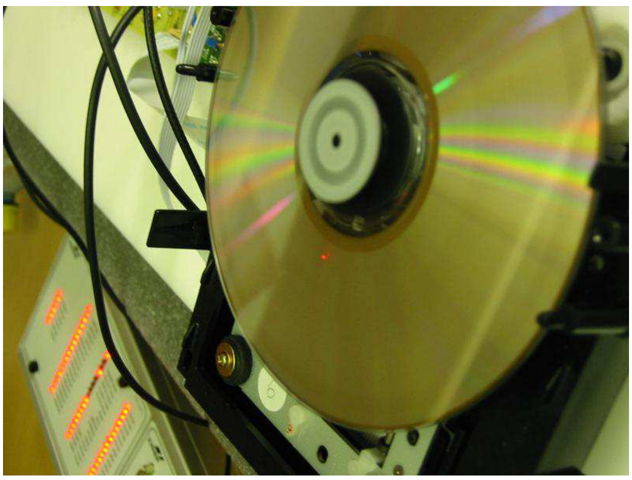
The DVD-reader tracking problem

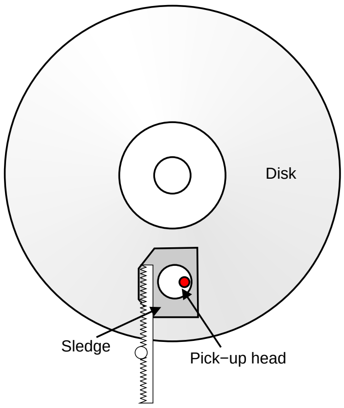


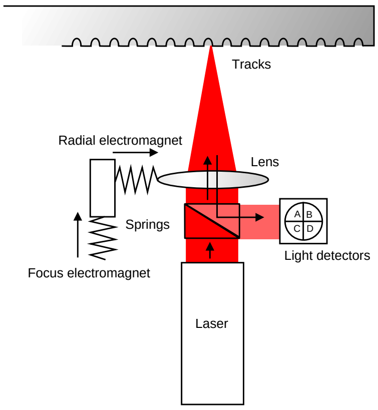
- 3.5 m/s speed along track
- 0.022 μm tracking tolerance
- 100 μm deviations at 23 Hz due to assymetric discs

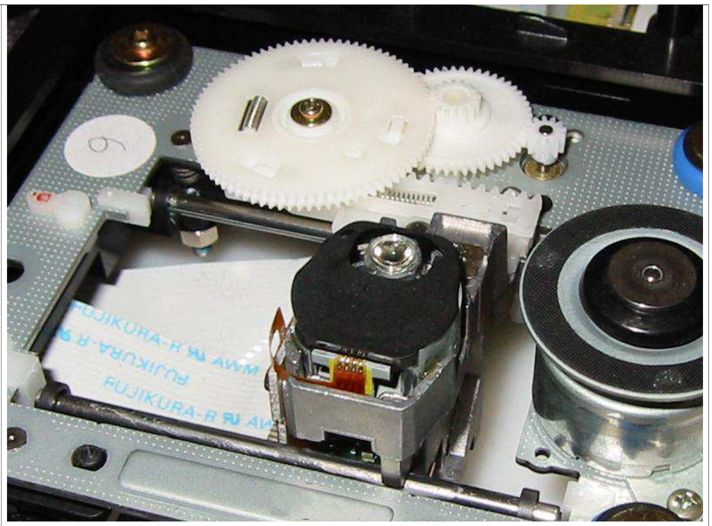
DVD Digital Versatile Disc, 4.7 Gbytes
CD Compact Disc, 650 Mbytes

Can you see the laser spot?

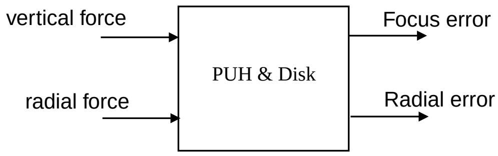




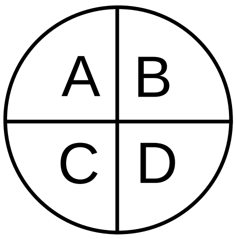




Input-output diagram for DVD control



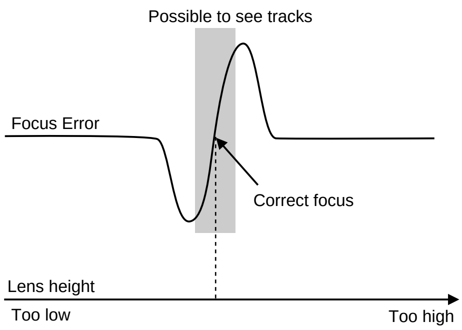
The four photo detectors



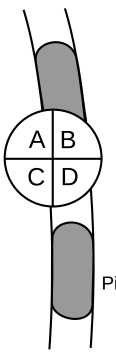
focus error = (A+D) – (B+C)

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

Focus error signal



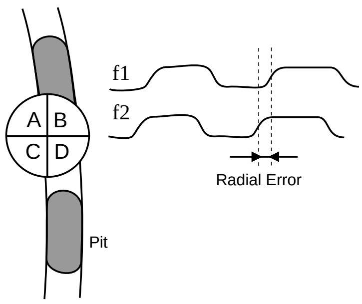
Radial error by push-pull



Look at

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

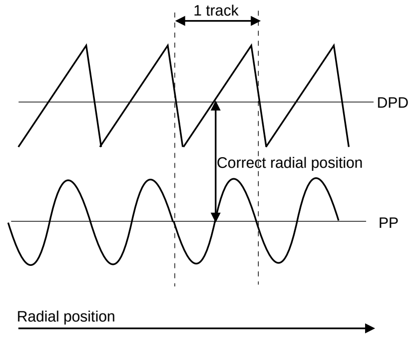
Radial error by phase-difference (DPD)



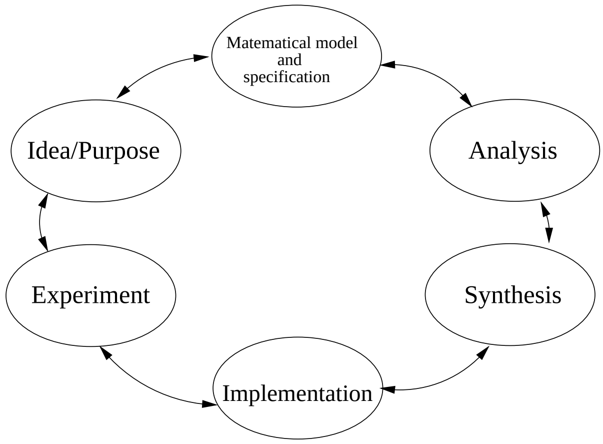
$$f_1 = A + D, \qquad f_2 = B + C$$

Error signal RE created be time difference

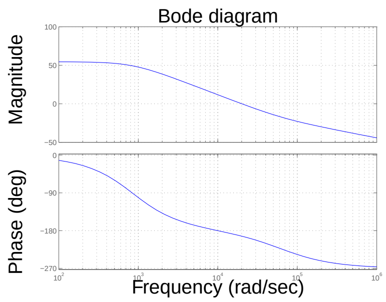
Radial error signals



Note: Larger linear error region if using DPD.

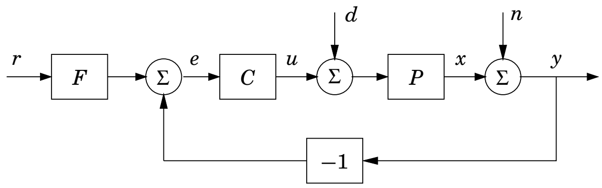


Experimental frequency response model



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

What Signals are Relevant for Focus Control?



Specifications

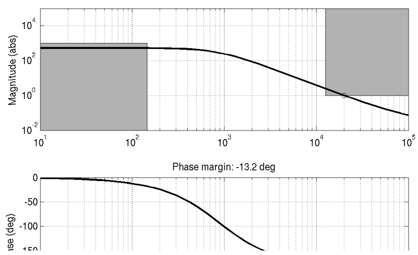
Cancel disturbances due to disc assymmetry

$|C(i\omega)P_f(i\omega)| \geq 1000$ for $\omega \leq 23.1$ Hz

Reject measurement noise

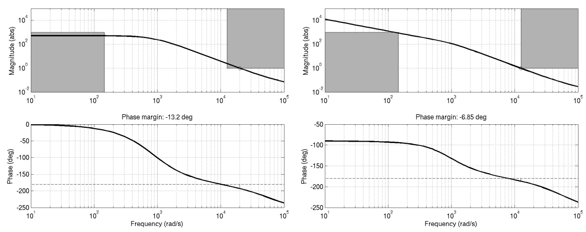
$|C(i\omega)P_f(i\omega)| \leq 1$ for $\omega > 2$ kHz

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



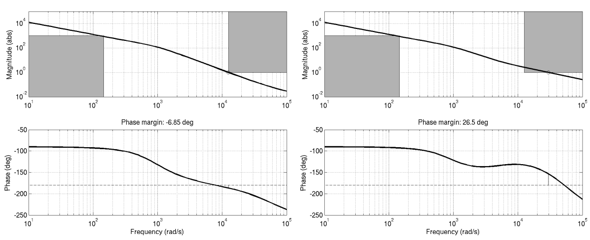
First Order Lag Compensator

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

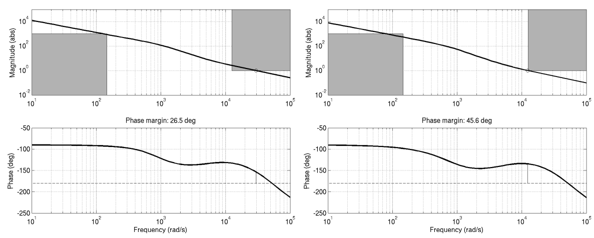
Further compensation is needed for stability. A lead filter to increase the phase near 2 kHz; $C_2(s) = 0.4\frac{s+600}{s}\frac{1+s/5000}{1+s/50000}$.



Adjust gain

The gain needs to be adjusted at high frequencies.

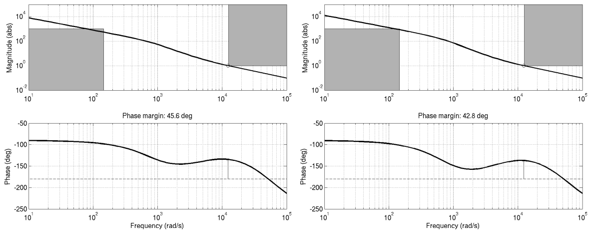
Now the closed loop system is stable with good margins, but the gain at 23.1 Hz is still too low, just 100 instead of 1000;



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
$C(s) = K\left(\frac{1}{sT_i} + \frac{sT_d}{1+sT_d/N}\right)$.



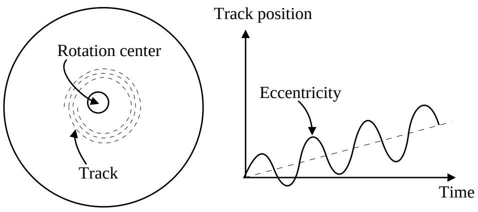


Figure: The disc is often a bit eccentric (i.e. not rotating around the track center). The resulting track position, which the Pick-Up-Head has to follow, is a sinus-like.

Radial control

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

The Focus control problem is essential to solve first

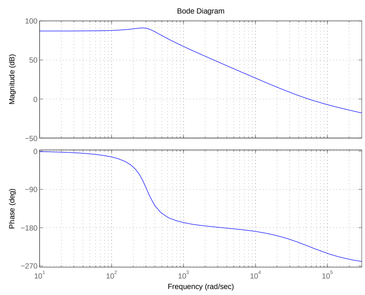
Tracking via

- 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)

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)

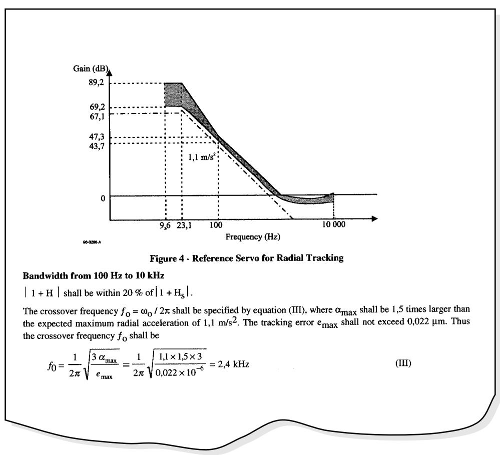


Figure 4 - Reference Servo for Radial Tracking

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?

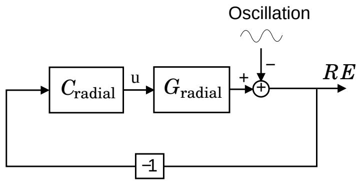


Figure: A model of how the disk oscillation affects the system. For example, if the oscillation offset at some point in time is +6.2 tracks, the DVD radial servo has to be at +6.2 tracks too to have zero RE.

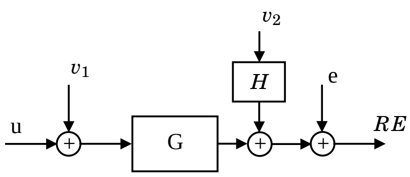


Figure: Noise model: There is both white process noise v_1, and a track-offset which is modeled as the white noise v_2 through a filter H.

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.

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 .

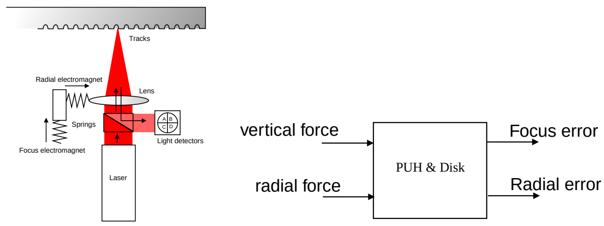
$$w_1 = G_1(p)v_1, \qquad w_2 = G_2(p)v_2$$

Make a state space realization of G_1 and G_2 and extend the system description with these states

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

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.



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

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