FRTN10 Multivariable Control, Lecture 5

Automatic Control LTH, 2017

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 player
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)

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)

Lecture 5 – Outline

1. Case study: Control of a DVD player
2. Review of cascade and midranging control

Case Study: Control of a DVD player

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

Based on work by Bo Lincoln

The DVD player 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 up to 25 times per second

Good luck!

The DVD player 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 up to 25 times per second

Good luck!

The DVD player 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 up to 25 times per second

Good luck!

The DVD player 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 up to 25 times per second

Good luck!

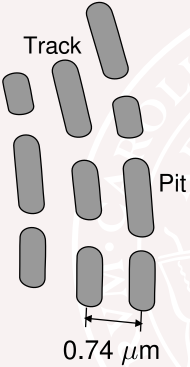
The DVD player tracking problem

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 up to 25 times per second

Good luck!

The DVD player tracking problem



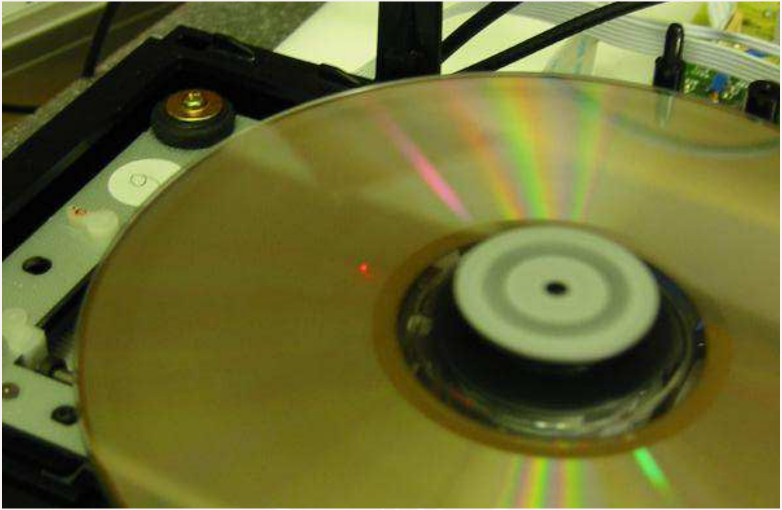
- 3.5 m/s speed along track
- 0.022 μm tracking tolerance
- 100 μm deviations at 10–25 Hz due to asymmetric discs

DVD Digital Versatile Disc, 4.7–8.5 GB

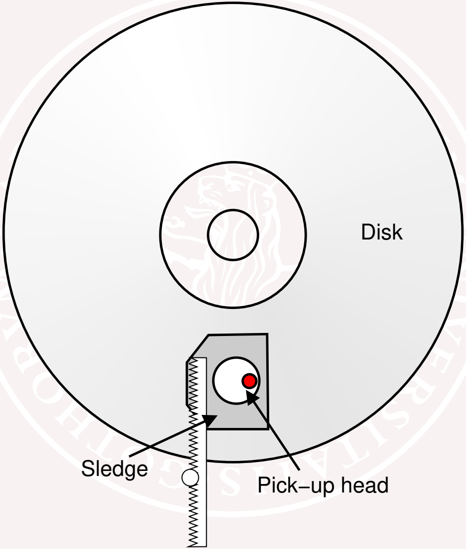
CD Compact Disc, 650–800 MB

Blu-ray 25–400 GB

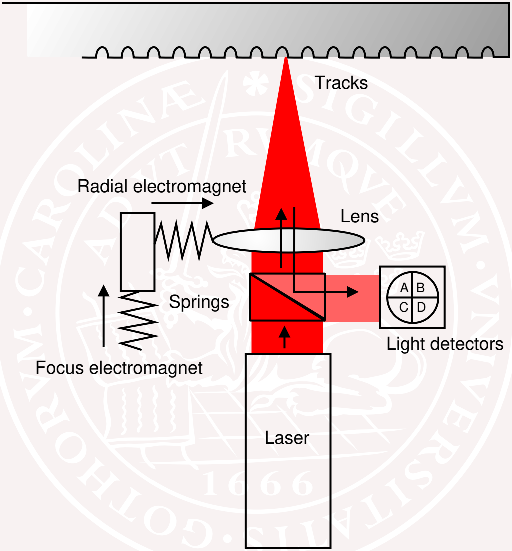
Can you see the laser spot?



The DVD Pick-Up Head

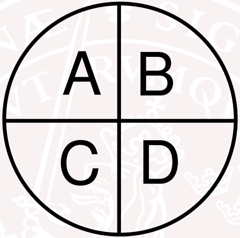



FUJIKURA-R


Tracks
Radial electromagnet
Lens
A
B
C
D
Springs
Light detectors
Focus electromagnet
Laser

Input-output diagram for DVD control

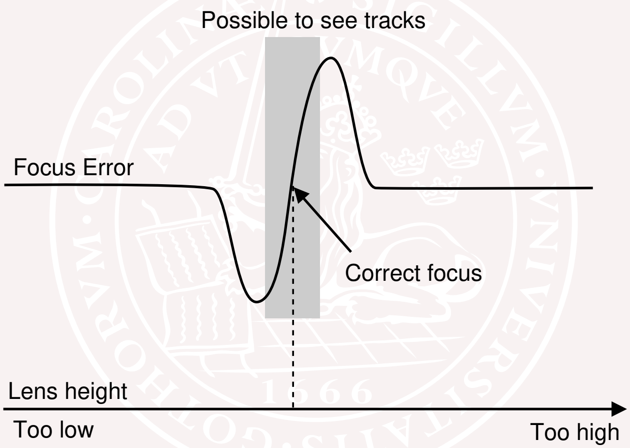
The four photo detectors



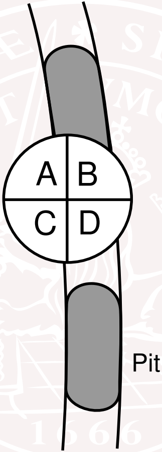
focus error = (A+D) – (B+C)

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

Focus error signal



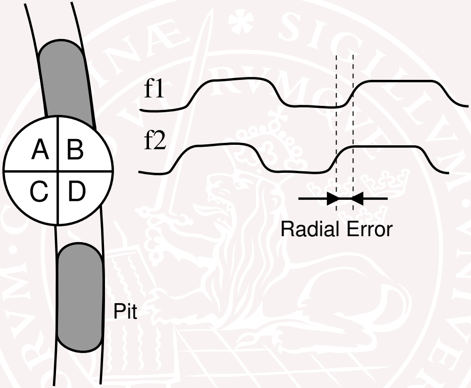
Radial error by push-pull



Look at

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

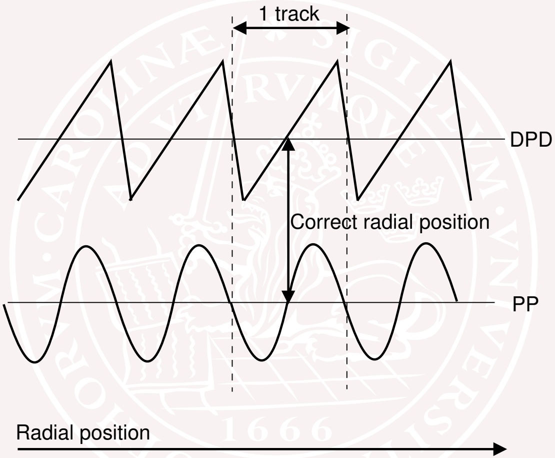
Radial error by phase difference



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

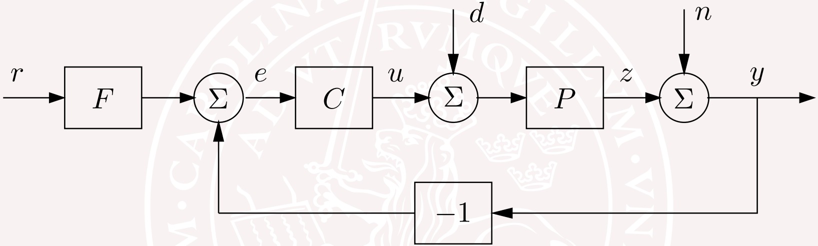
Error signal RE created by time difference

Radial error signals



Note: Larger linear error region if using phase difference.

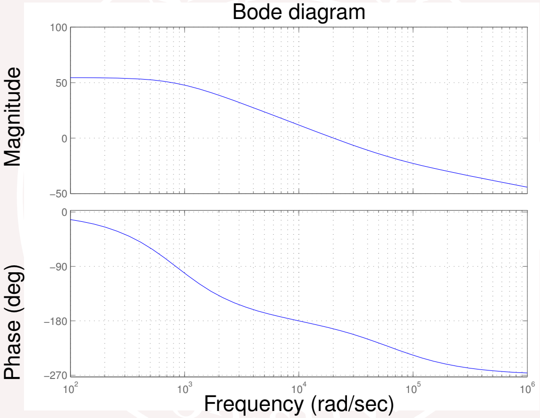
Focus control design



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

Focus process model

Model obtained using system identification:



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

From DVD standard ECMA-267

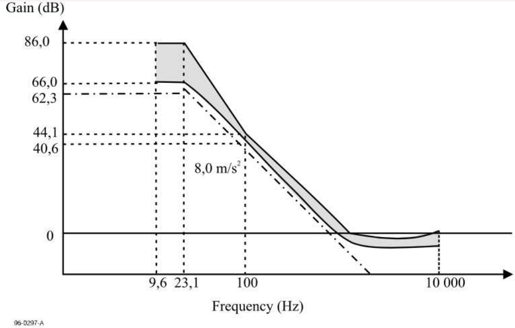


Figure 3 - Reference Servo for axial tracking

Bandwidth 100 Hz to 10 kHz

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

The crossover frequency $f_o = \omega_o / 2\pi$ shall be specified by equation (II), where α_{max} shall be 1,5 times larger than the expected maximum axial acceleration of 8 m/s^2. The tracking error e_{max} shall not exceed 0,23 µm. Thus the crossover frequency f_o shall be

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3\,\alpha_{max}}{e_{max}}} = \frac{1}{2\pi}\sqrt{\frac{8\times 1{,}5\times 3}{0{,}23\times 10^{-6}}} = 2{,}0\text{ kHz} \qquad \text{(II)}$$

http://www.ecma-international.org/publications/standards/Ecma-267.htm

Specifications

- Cancel disturbances due to disc asymmetry

$$|P(i\omega)C(i\omega)| \geq 2000 \qquad \text{for } f \leq 23 \text{ Hz}$$

- Robustness towards model errors, rejection of meas. noise

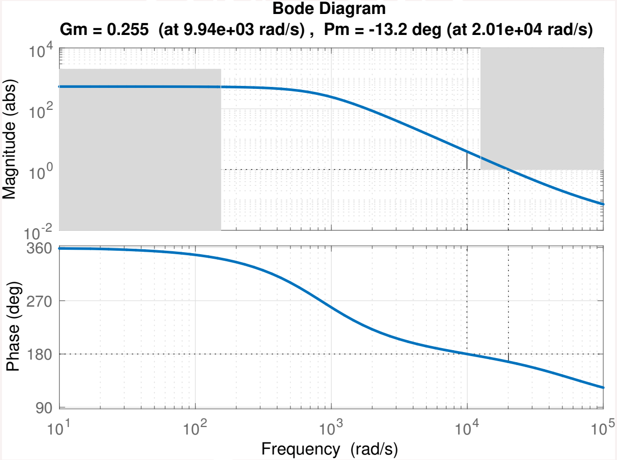
$$|P(i\omega)C(i\omega)| \leq 1 \qquad \text{for } f > 2 \text{ kHz}$$

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

- Good stability margins

Open-Loop System

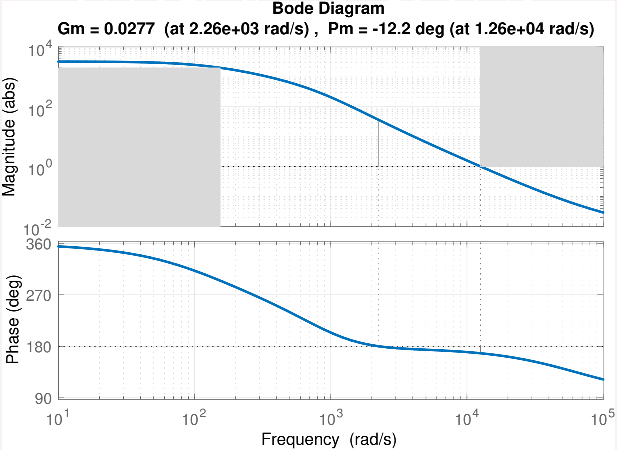
Bode plot of $P(s)$ with stability margins and specifications:



Can a P-controller solve the problem?

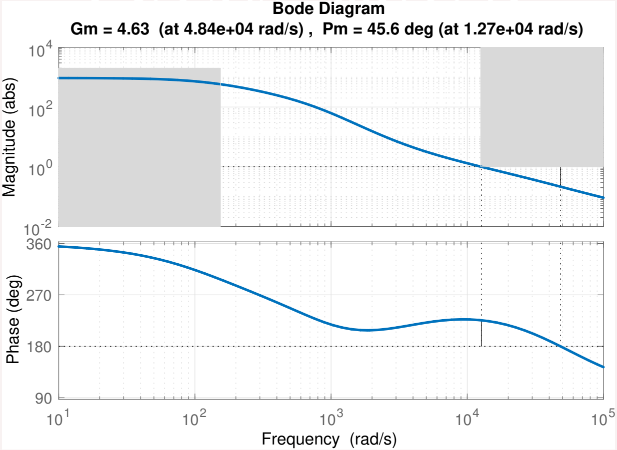
Add Lag Compensator

Use lag filter with $M = 15$ to increase gain below 23 Hz. The break point needs to be well below 2 kHz in order to avoid excessive phase lag at the cross-over frequency: $C(s) = KC_{lag}(s) = \frac{0.4037(s+1885)}{s+125.7}$



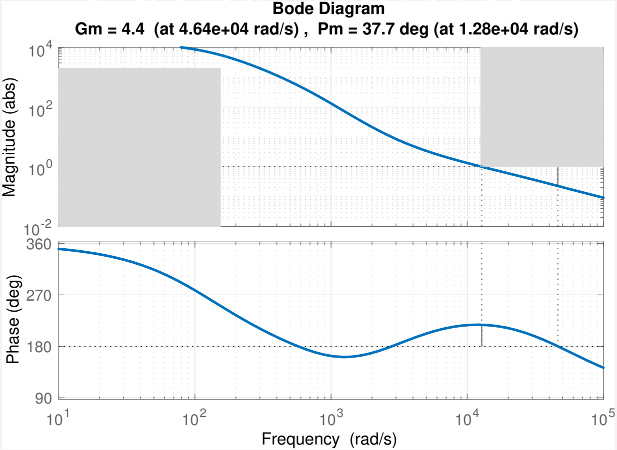
Add Lead Compensator

Use lead filter with $N = 12$ to increase phase by 57° at cross-over frequency. $C(s) = KC_{lag}(s)C_{lead}(s) = \frac{1.398(s+1885)(s+3228)}{(s+125.7)(s+43530)}$



Add Another Lag Compensator

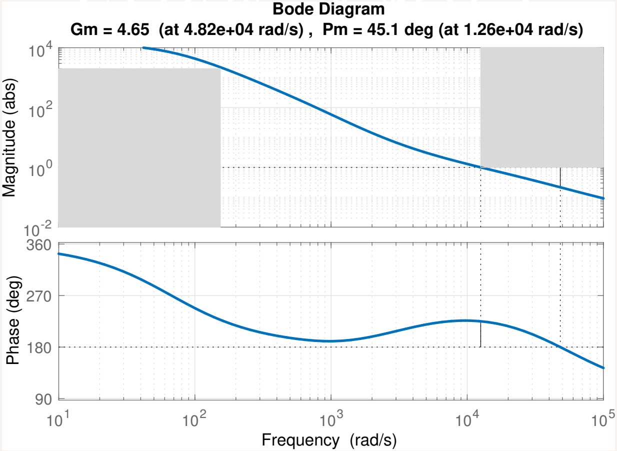
Low-frequency gain too low. Add another lag compensator with same parameters: $C(s) = KC_{lag}^2(s)C_{lead}(s) = \frac{1.398(s+1885)^2(s+3628)}{(s+125.7)^2(s+43530)}$



Final Adjustments

Phase margin too small again. Lower the break frequency of the lag filters to recover some phase:

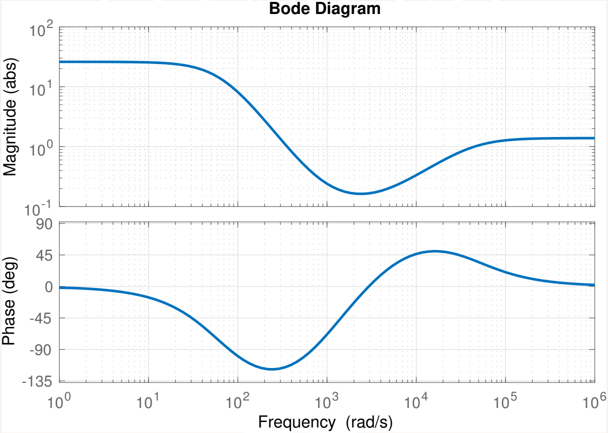
$$C(s) = KC_{lag}^2(s)C_{lead}(s) = \frac{1.397(s+1005)^2(s+3628)}{(s+67.02)^2(s+43530)}$$



Final Controller

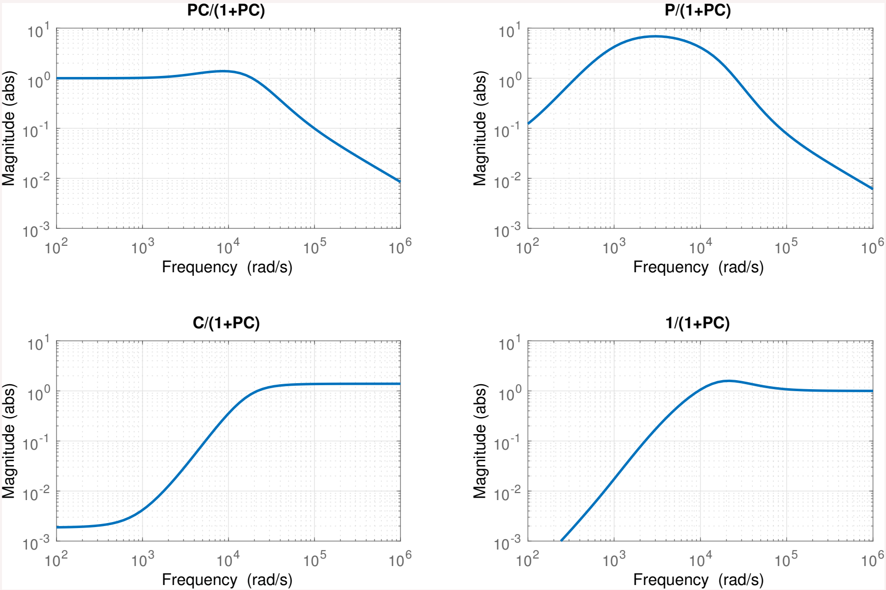
Bode diagram of final controller

$$C(s) = KC_{lag}^2(s)C_{lead}(s) = \frac{1.397(s+1005)^2(s+3628)}{(s+67.02)^2(s+43530)}$$



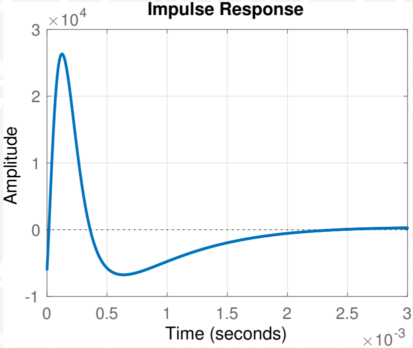
(Would be good to add another pole to have high-frequency roll-off)

Gang of Four



PC/(1+PC)
P/(1+PC)
C/(1+PC)
1/(1+PC)
Magnitude (abs)
Frequency (rad/s)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

Response to impulse load disturbance



Radial control

Make the laser follow the track by moving “sideways”/radially

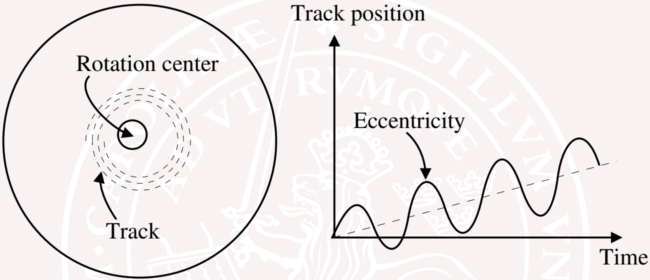
It is essential to solve the Focus control problem first

Tracking via two parallel actuators (midranging):

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

Disturbances:

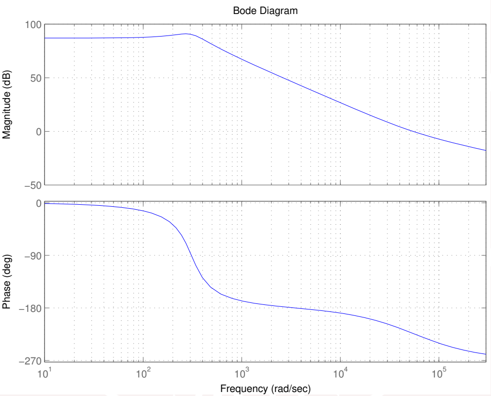
- eccentricity (up to 100 tracks in one rotation)
- physical vibrations of DVD player
- noise, dirt, etc.



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.

From DVD standard ECMA-267

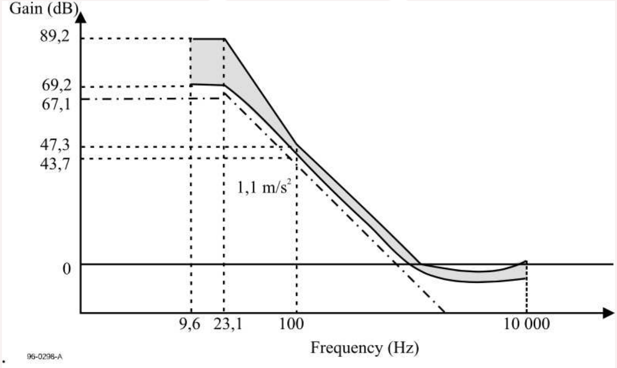


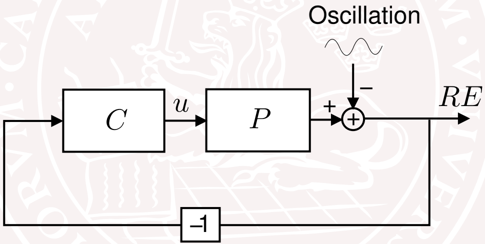
Figure 4 - Reference Servo for Radial Tracking

Similar requirements as for the axial (focus) tracking

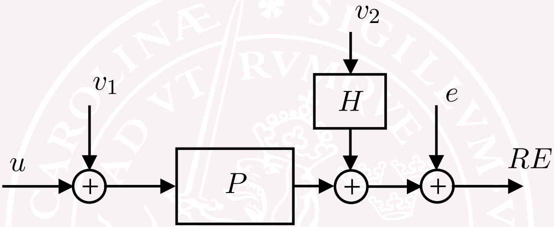
Many possible design methods (loop shaping, pole placement, LQG)

Problem with sinusoidal output disturbance

The eccentricity causes problems (at about 10–25 Hz and magnitude up to 100 tracks). Cannot be exactly modeled due to uncertainty.



Stochastic disturbance modeling



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.

The filter H should have a high gain in the frequency range where the oscillation acts (bandpass filter)

Kalman filter + state feedback then solves the problem elegantly

Further reading

- 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,

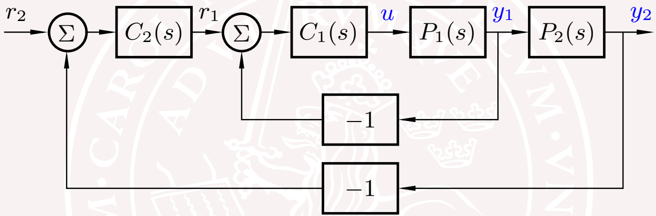
`http://www.ieeecss.org/CSM/library/2008/june08/11-June08ApplicationsOfControl.pdf`

Lecture 5 – Outline

1. Case study: Control of a DVD player
2. Review of cascade and midranging control

Cascade control

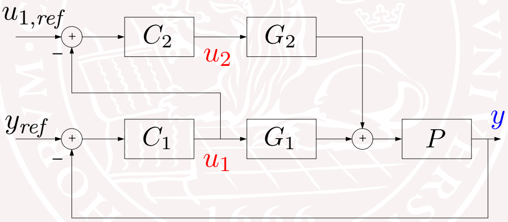
For systems with one control signal and two (or more) outputs:



- $C_1(s)$ 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)

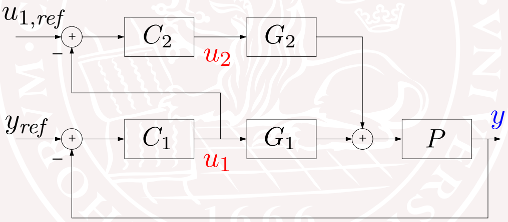


C_2 acts on a much slower time-scale than C_1

$u_{1,ref}$ should be set at the middle of u_1's operating range

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)

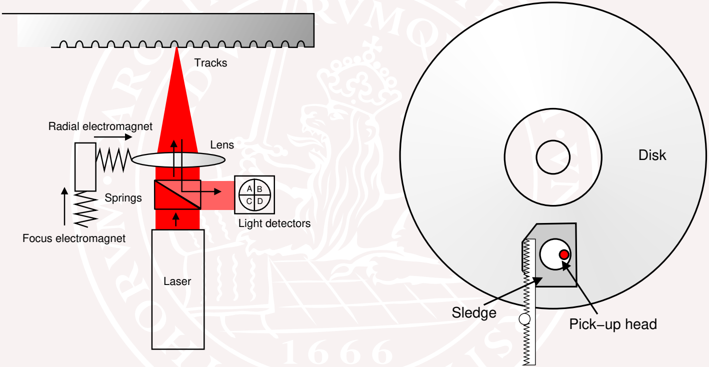


C_2 acts on a much slower time-scale than C_1

$u_{1,ref}$ should be set at the middle of u_1's operating range

Midranging Control – 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).