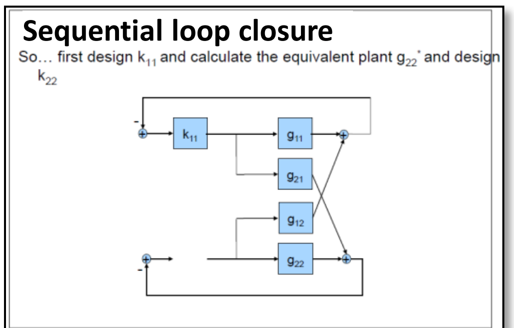
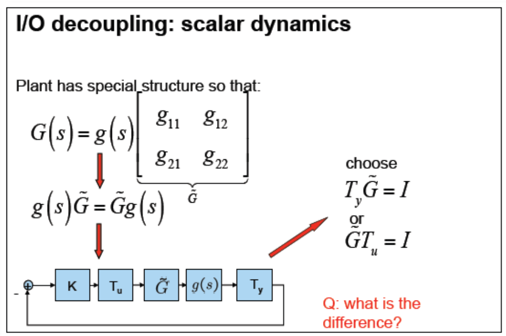
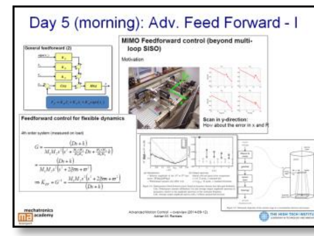
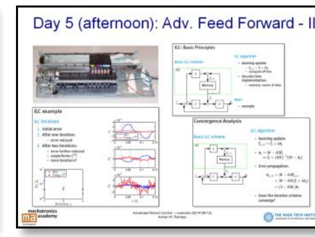
Advanced Motion Control

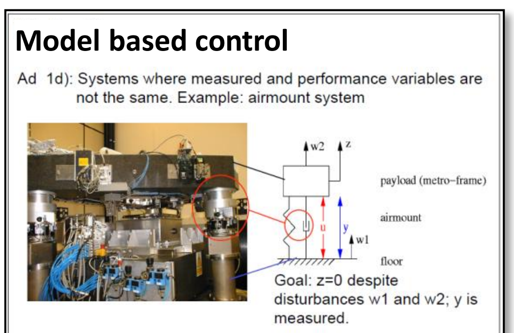
Overview of training

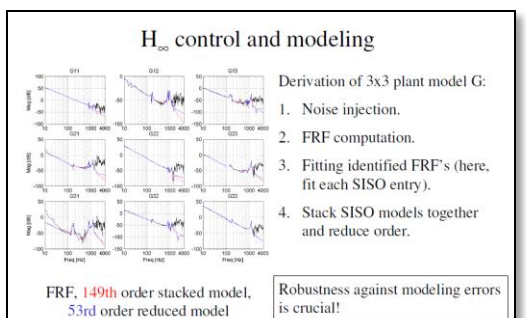












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Contents

- Mechatronics Training Curriculum
- Details of Course *Advanced Motion Control Tuning*

Mechatronics Training Curriculum

Premium	Workshop Mechatronics System Design – **On request**
Premium / Advanced	Advanced Motion Control – **5 days**; Advanced Feedforward & Learning Control – **3 days**; Passive Damping for High Tech Systems – **3 days**; Masterclass Design Principles – **On request**
Advanced	Advanced Mechatronic System Design – **6 days**
Standard	Motion Control Tuning – **5 days**; Dynamics and Modelling – **3 days**; Design Principles for Precision Eng. – **5 days**; Basics and Design for Ultra Clean Vacuum – **4 days**; Experimental Techniques in Mechatronics – **3 days**; Metrology & Calibration of Mechatronic Systems – **3 days**; Actuation and Power Electronics – **3 days**; Machine Vision for Mechatronic Systems – **2 days**; Thermal Effects in Mechatronic Systems – **3 days**
Basic	Mechatronics System Design – part 2 – **5 days**; Mechatronics System Design – part 1 – **5 days**

Start

<u>Relevant partner trainings:</u>
Applied Optics, Electronics for non-electrical engineers, System Architecture, Soft skills for technology professionals, …

www.mechatronics-academy.nl

Mechatronics Academy

- In the past, many trainings were developed within Philips to train own staff, but the training center CTT stopped.
- **Mechatronics Academy B.V.** has been setup to provide continuity of the existing trainings and develop new trainings in the field of precision mechatronics. It is founded and run by:
    - Prof. Maarten Steinbuch
    - Prof. Jan van Eijk
    - Dr. Adrian Rankers
- We cooperate in the **High Tech Institute** consortium that provides sales, marketing and back office functions.

Advanced Motion Control

Course Directors / Trainers

Course Director(s)

- Dr.ir. Tom Oomen (TU/e)
- Dr.ir. Adrian Rankers (Mechatronics Academy)

Teachers

- TU/Eindhoven:
  - Prof.dr.ir. M. Steinbuch, Dr. ir. T. Oomen, Dr.ir. R.J.R. van der Maas
  - ir. L.L.G. Blanken, ir. E. Evers, ir. R. de Rozario, ir. R. Voorhoeve, ir. J.C.D. van Zundert
- Other:
  - Prof. Dr.ir. M.F. Heertjes (ASML + TU/e)
  - Dr.ir. M.J.M. van de Wal (ASML)
  - dr. ir. W. Aangenent (ASML)
  - Dr.ir. D. Rijlaarsdam (Additive Industries)

Program

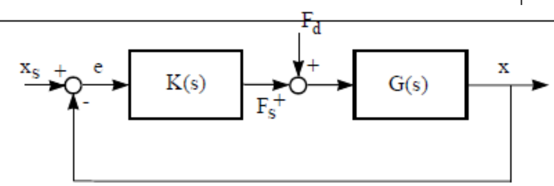
Day	Timing	Topic
1	Morning	• Introduction / Who is who / Program / Goals… • Refreshing SISO Motion Control Design • SISO experiment on MIMO set-up
	Afternoon Evening	• Modal Description • SIMO experiments (1 in, 2 out) + MIMO experiments • Linear Algebra • Dinner
2	Morning	• Stability • Interaction Analysis
	Afternoon	• Static Decoupling (theory & experiments)
3	Morning	• MIMO – how to ? • MIMO identification • Case study: H-drive
	Afternoon	• Exercises case study • Sequential loop design (theory & experiments)
4	Morning	• Sequential loop design exercises • Model based control
	Afternoon	• Model based control - exercise
5	Morning	• Non-Linear Identification • Advanced Feed Forward
	Afternoon	• Identificaton for Control and ILC • Challenges in Motion for High Tech

Day 1 (morning): Recap SISO …

- Introduction / goals
- Recap SISO approach
  - Theory
  - Practice

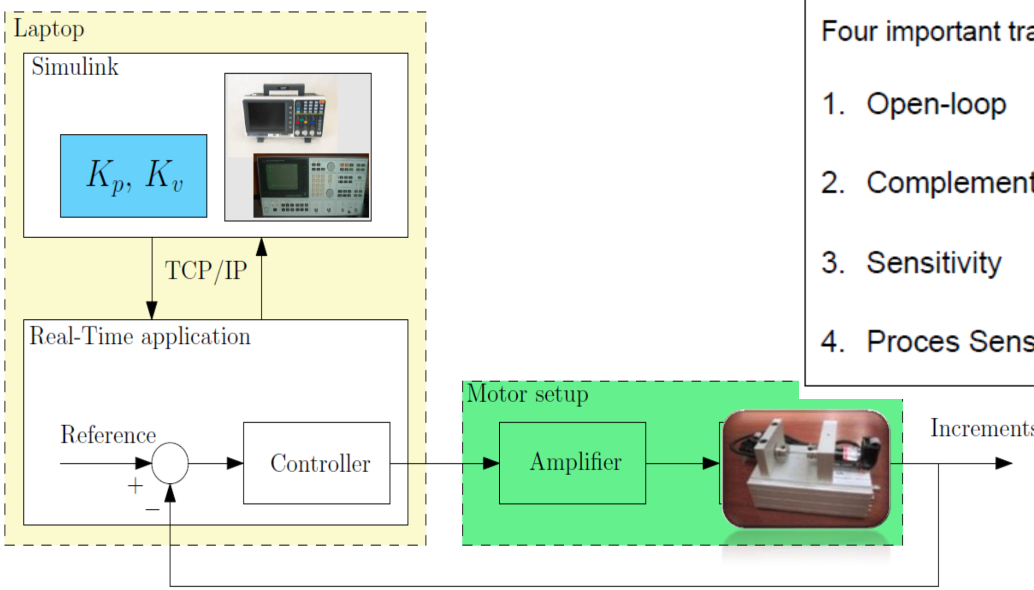
MIMO step-wise design approach

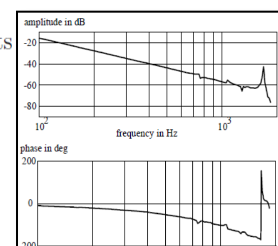
1. Measure/identify the mimo FRF data
2. Use interaction measures to assess the amount of interaction
3. Investigate decoupling
4. Investigate sequential loop closing
5. Use norm based design

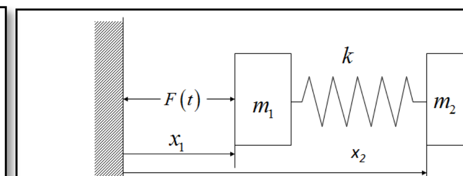


Four important transfer functions:

1. Open-loop $L(s) = G(s)K(s) = K(s)G(s)$ Only SISO!
2. Complementary Sensitivity $T(s) = \frac{x}{x_s}(s) = \frac{G(s)K(s)}{1+G(s)K(s)}$
3. Sensitivity $S(s) = \frac{e}{x_s}(s) = \frac{1}{1+G(s)K(s)}$
4. Proces Sensitivity $S_p(s) = \frac{x}{F_d}(s) = \frac{G(s)}{1+G(s)K(s)}$







The equations of motion: $F - k(x_1 - x_2) = m_1\ddot{x}_1$
$+k(x_1 - x_2) = m_2\ddot{x}_2$

Day 1 (afternoon): First steps …

- Modal Description
- SIMO experiments (1 in, 2 out)
- Linear Algebra

Matrix Gain

$y = Ax \quad \text{"(gain of } A\text{)"} \quad \frac{\|y\|_2}{\|x\|_2}$

$\begin{bmatrix}1\\3\end{bmatrix} = \begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} \qquad \|y\|_2 = \sqrt{10}\,\|x\|_2$

$\begin{bmatrix}2\\4\end{bmatrix} = \begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}\begin{bmatrix}0\\1\end{bmatrix} \qquad \|y\|_2 = \sqrt{20}\,\|x\|_2$

'gain depends on the direction of the input vector !

Singular values of *A*

$$\underline{\sigma}(A) \le \frac{\|Ax\|_2}{\|x\|_2} \le \bar{\sigma}(A)$$

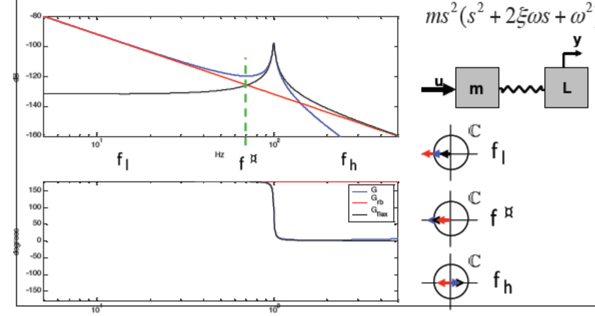
If we take for x an orthonormal eigenvector of *A* then

$$\underline{\sigma}(A) \le \frac{\|\lambda x\|_2}{\|x\|_2} \le \bar{\sigma}(A)$$

$$\underline{\sigma}(A) \le |\lambda| \le \bar{\sigma}(A)$$

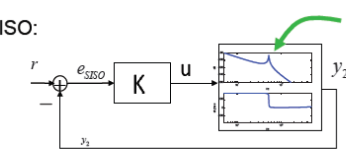
Non-collocated

$$G(s) = \frac{1}{ms^2} + \frac{-1}{m(s^2 + 2\xi\omega s + \omega^2)} = \frac{2\xi\omega s + \omega^2}{ms^2(s^2 + 2\xi\omega s + \omega^2)}$$



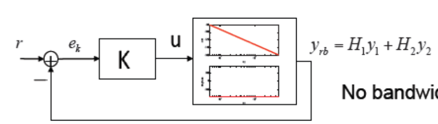
SIMO experiment

SISO:



Bandwidth limitation!

SIMO:

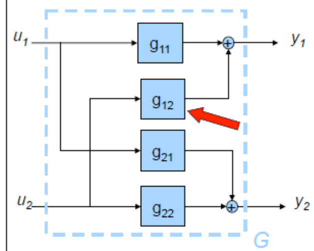


No bandwidth limitation!

Day 2 (morning): Stability & Interaction

- Stability
- Interaction Analysis

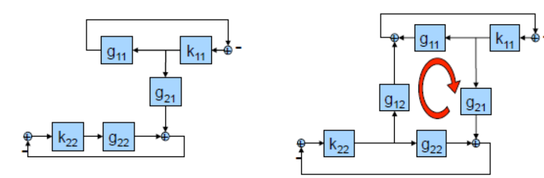
What is interaction?



$$y_1 = g_{11}u_1 + g_{12}u_2$$
$$y_2 = g_{21}u_1 + g_{22}u_2$$
$$\rightarrow y_1 = f(u_1, u_2)$$

Decoupled: $y_1 =$

Types of interaction



- no stability problem
- perfo

- stability problem!

Interaction index

$$G_{eq2} = g_{22} - \underbrace{\frac{g_{12}k_{11}g_{21}}{1+g_{11}k_{11}}}_{\text{due to interaction}}$$

$$= g_{22}\left(1 - \underbrace{\frac{g_{12}g_{21}}{g_{11}g_{22}}}_{\phi}\frac{g_{11}k_{11}}{1+g_{11}k_{11}}\right) = g_{22}(1-\phi t_{11})$$

Interaction index $\phi = \frac{g_{12}g_{21}}{g_{11}g_{22}} \approx 0$

Relative gain $\Lambda_{22} = \frac{1}{1-\phi} \approx\sim 1$

No interaction!

Graphical evaluation of stability

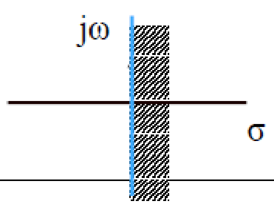
Open-loop system G(s)K(s) is stable!

For increasing frequency along the curve of $\det\left[I_m + G(s)K(s)\right]$ in the complex plane, the point (0,0) should stay at the left hand side of the curve.

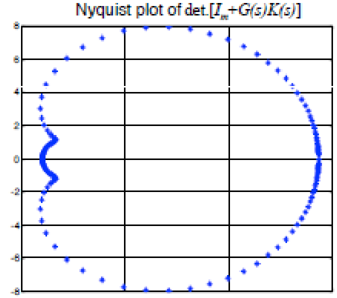
The Nyquist plot should not encircle the point (0,0)

$\det.[I_m + G(s)K(s)]$ with s=jω

s-plane



Nyquist plot of $\det.[I_m+G(s)K(s)]$



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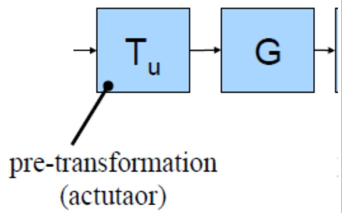
Day 2 (afternoon): Static Decoupling

Why?

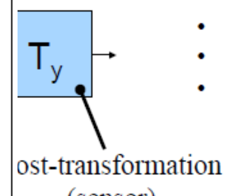
- transform to decoupled form -> independent SISO design
- change of control variables (sometimes nice)
- possible interaction in other transferfunctions



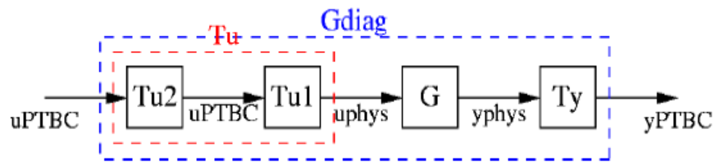
How?

- only static decoupling
- decoupling with both T_u,T_y?
- Often many solutions: finding one is hard
- Use (engineering?) creativity…

- kinematics
- physical model
- symmetry
- tricks

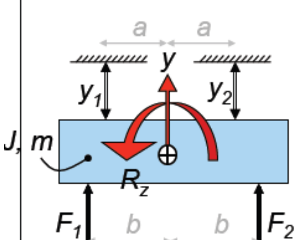


Practical decoupling procedure



1. Derive rigid-body model for G with physical actuator and sensor signals as inputs and outputs.
2. Transform physical sensor coordinates into coordinates of Point To Be Controlled (PTBC): T_y.
3. Derive T_{u1} based on inversion of T_y*G.
4. Implement T_{u1} and T_y and identify FRF of G.
5. Calibration of $T_{u=} T_{u1}$*T_{u2} via T_{u2} based upon FRF of G.

I/O decoupling: geometry



Q: Der
is d
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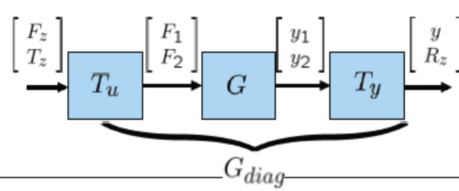
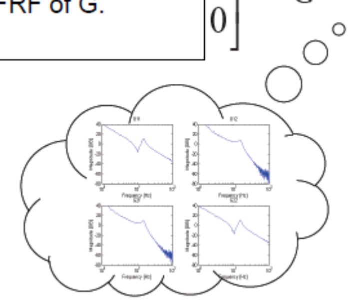
only



metry

that:

$$\ldots \begin{matrix} 1 \\ 0 \end{matrix}\Big] \rightarrow G = \begin{bmatrix} G_1 & G_2 \\ G_2 & G_1 \end{bmatrix} \quad (1)$$



Question1: What are the eigenvectors and eigenvalues of G?

Question 2: decouple G

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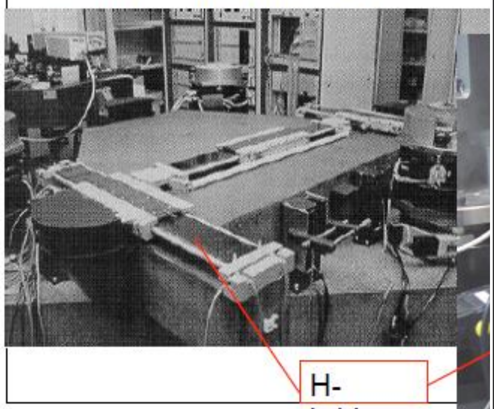
Day 3 (morning): MIMO Identification

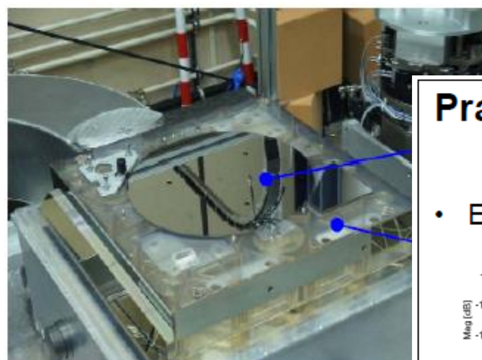
Rigid-body-dominated MIMO motion systems

- **H-bridges:** controlled in horizontal plane.
- Example: in wafer stages:



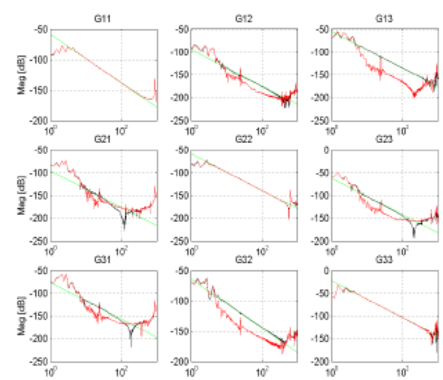
Rigid-body-dominated MIMO motion systems

- **Single mass devices**: controlled in 6DOF's.
- Example: in wafer stages:



Practical decoupling procedure

- Example of calibration T_{u2}:



- FRF with T_{u2}=I
- $\frac{1}{(j\omega)^2} \cdot \tilde{G}_{FRF}$
- FRF with calibrated T_{u2}:

$$T_{u2} = \begin{bmatrix} 1.0000 & -0.0033 & -1.3917 \\ 0.0122 & 1.0000 & -0.6862 \\ 0.0021 & -0.0087 & 1.0000 \end{bmatrix}$$

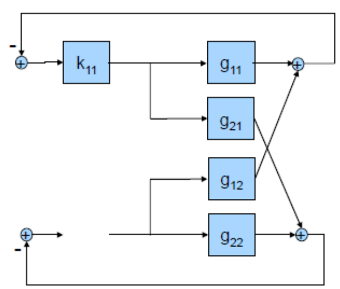
Day 3 (afternoon): MIMO continued …

- Exercises
- Sequential Loop Design

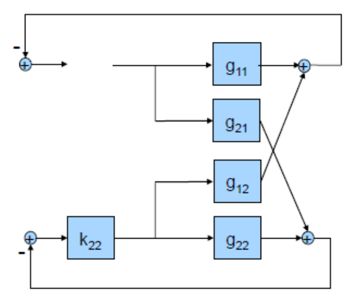
Sequential loop closing - key idea

First close one loop stable, then the overall stability is determined by closing the other loop with the equivalent plant!

So… first design k_{11} and calculate the equivalent plant g_{22}^* and design k_{22}



Or.. first design k_{22} and calculate the equivalent plant g_{11}^* and design k_{11}



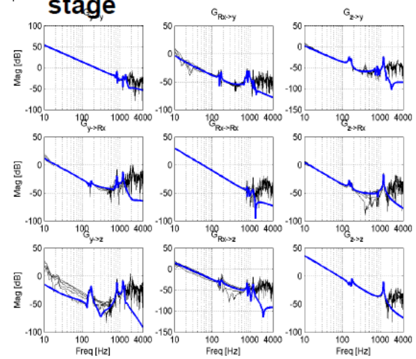
Summary / Remarks

- the only good way to do SISO design for a MIMO plant!
- everything can be done usings FRFs only!
- in most cases 2x2 subproblems can be separated, if not….
- reverse order and see the difference
- margins are tricky…always check closed loop MIMO sensitivity S(s)!

Day 4 (morning): Model Based

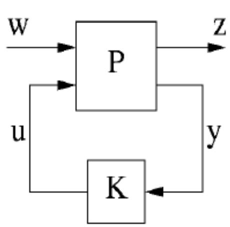
- Exercise Sequential Loop Shaping
- Model Based

Application H_∞/μ control design to wafer stage



Starting point for MIMO μ-synthesis is 53rd order plant model and set of FRF's at various positions.

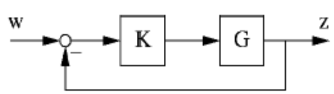
The standard plant set-up



- y and z need not be equal
- K can be MIMO and non-squ

Norm-based control

Temporary simplifying assumption: M is SISO, *e.g.*, M is the complementary sensitivity function T:



$$z = T \cdot w = GK(I+GK)^{-1} \cdot$$

p-norm for stable M:

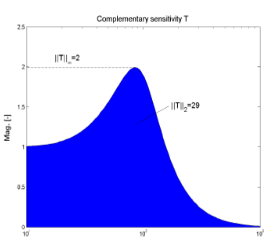
$$\| M \|_p := \sqrt[p]{\int_{-\infty}^{\infty} | M(j\omega) |^p \, d\omega}$$

Mostly used system norms:

- H_2-norm: $\| M(s) \|_2 := \sqrt[2]{\int_{-\infty}^{\infty} | M(j\omega)}$
- H_∞-norm: $\| M(s) \|_\infty := \sup_\omega | M(j\omega)$

Norm-b

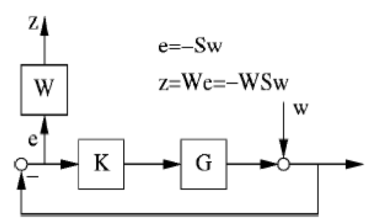
Interpretation of the H_∞-norm and H_2-norm

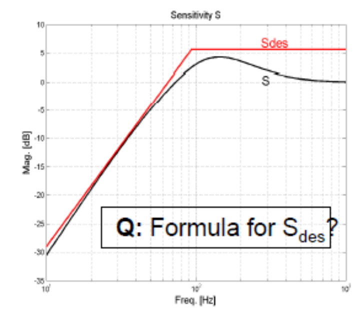


- H_∞-norm: peak of the magnitude plot.
- H_2-norm: "surface" below the magnitude plot

(square root of the squared surface).

Weighting filters in H_∞-optimization





Q: Formula for S_{des}?

- Specify |S| by $|S_{des}|$ $|S| < |S_{des}| \Leftrightarrow |S/S_{des}| < 1$
- Note z=-WSw, so with W=1/ $|S/S_{des}| < 1 \Leftrightarrow |WS| < 1$

S_{des}: $|WS| < 1 \; \forall \; \omega \Leftrightarrow \sup_\omega |WS| < 1 \Leftrightarrow \| WS \|_\infty < 1$

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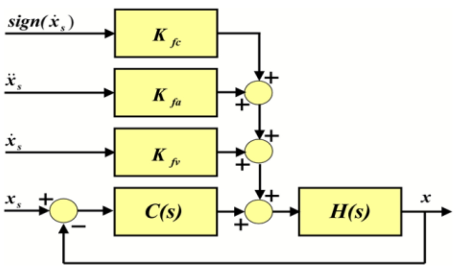
Day 4 (afternoon): Model Based Control …

Exercise

Day 5 (morning): Non-Linear & Adv. FF

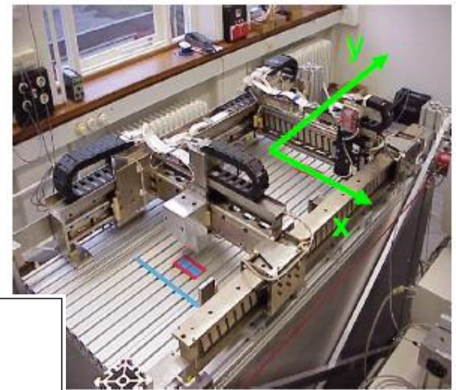
General feedforward (2)

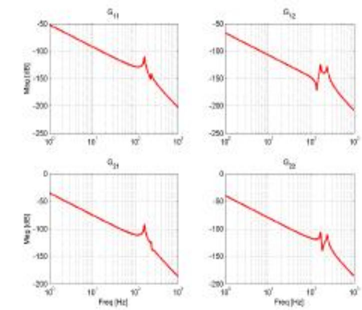


$$F_{ff} = K_{fa}\ddot{x}_s + K_{fv}\dot{x}_s + K_{fc}\,sign(\dot{x}_s)$$

MIMO Feedforward control (beyond multi-loop SISO)

Motivation





Scan in y-direction:
How about the error in x and R

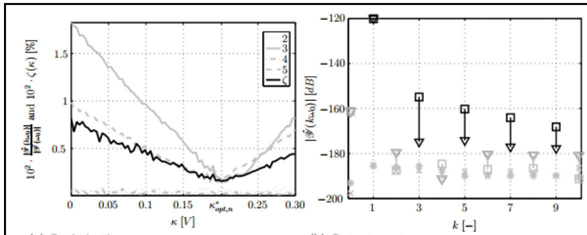
Feedforward control for flexible dynamics

4th order system (measured on load)

$$G = \frac{(Ds+k)}{M_1 M_2 s^2\left(s^2 + \frac{M_1+M_2}{M_1 M_2} Ds + \frac{M_1+M_2}{M_1 M_2} k\right)}$$

$$= \frac{(Ds+k)}{M_1 M_2 s^2\left(s^2 + 2\xi\varpi s + \varpi^2\right)}$$

$$\Rightarrow K_{FF} = G^{-1} = \frac{M_1 M_2 s^2\left(s^2 + 2\xi\varpi s + \varpi^2\right)}{(Ds+k)}$$



(a) Optimization
– Relative amplitude of the 2nd to 5th harmonic: $|\hat{\mathscr{Y}}(k\xi_0)|/|\hat{\mathscr{Y}}(\xi_0)|$
– Performance measure $\zeta(\kappa)$ (Def. 5.4).

(b) Output spectrum
(black) odd and (grey) even components
$\kappa = 0$: □ mean, ∗ standard dev.
$\kappa = \kappa^*_{opt,n}$: ▽ mean, × standard deviation.

Figure 5.4: Optimization of feed forward control, based on frequency domain data (low gain feedback). 5.4a: Performance measure (Definition 5.4) and average output amplitude spectrum at harmonics, relative to the amplitude spectrum at the excitation frequency. 5.4b: Average output amplitude spectra with / without optimal feed forward.

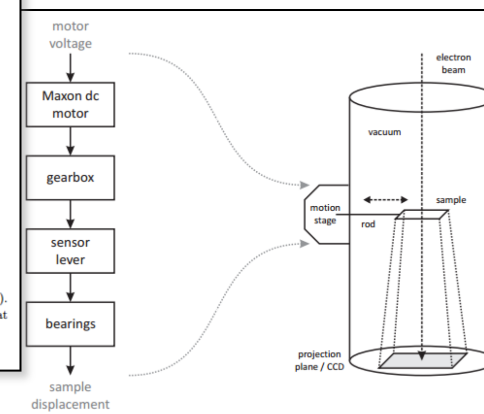
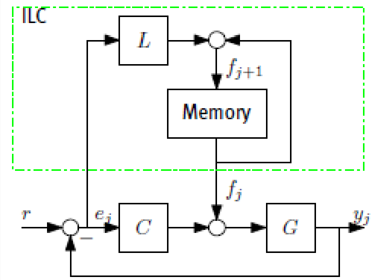


Figure 5.2: Schematic depiction of the motion stage in a transmission electron microscope.

Day 5 (afternoon): Identification for Control / ILC & Challenges in High Tech

ILC: Basic Principles

Basic ILC scheme



ILC algorithm

- learning update:
  - $f_{j+1} = f_j + Le_j$
  - compute off-line
- discrete time implementation:
  - memory: vector of data

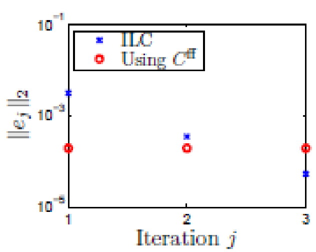
Next

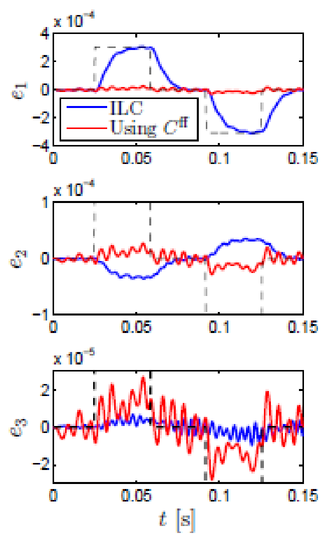
- example

ILC example

ILC iterations

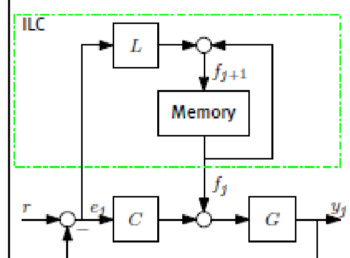
1. Initial error
2. After one iteration:
   - error reduced
3. After two iterations:
   - error further reduced
   - outperforms C^{ff}!
   - more iterations?





Convergence Analysis

Basic ILC scheme



ILC algorithm

- learning update: $f_{j+1} = f_j + Le_j$
- $e_j = Sr - GSf_j$
  $\Rightarrow f_j = (GS)^{-1}(Sr - e_j)$
- Error propagation:

$$\begin{aligned} e_{j+1} &= Sr - GSf_{j+1} \\ &= Sr - GS(f_j + Le_j) \\ &= (1 - GSL)e_j \end{aligned}$$

- Does the iterative scheme converge?

Sign-up for this training

Via the website of our partner

High Tech Institute