TU/e

Advanced Motion Control

Maarten Steinbuch
Control Systems Technology
Department of Mechanical Engineering
Eindhoven University of Technology

APC workshop, Vancouver, may 2005

Contents

- background, motion systems
- control for dummies
- advanced motion control challenges
- embedded dynamical systems

Eindhoven University of Technology

- 9 scientific departments, 10 academic Bachelor programmes, 19 Master programmes, 3000 employees, 220 professors, 6800 students, 200 postgraduate students, 450 PhD students
- located in the Eindhoven-Aachen-Leuven triangle
- ‘mechatronics’ high tech industry:
- Philips, ASML, FEI, Assembleon

Mechanical Engineering Department

- 9 full prof., 60 senior research staff,
- 18 Post Docs, 105 PhD students,
- 700 BSc and MSc students

Structure of Mechanical Engineering

Thermo Fluids Engineering

Computational and Experimental Mechanics

Dynamical Systems Design

2 ‘theme Mastertracks’:
- Automotive Engineering Science
- Micro and Nano Technology

Mechanical Engineering Department

Automotive Engineering Science (2001)

(Sub)-Micron Technology (2003)

Dynamical Systems Design (DSD)	Thermo Fluids Engineering (TFE)	Computational & Experimental Mechanics (CEM)

TU/e - W : Full Chairs in DSD Division

- Dynamics and Control:
  Prof.Dr. Henk Nijmeijer
- Control Systems Technology:
  Prof.Dr.Ir. Maarten Steinbuch
- Systems Engineering :
  Prof.Dr.Ir. Koos Rooda

from Industry …

… to Academia

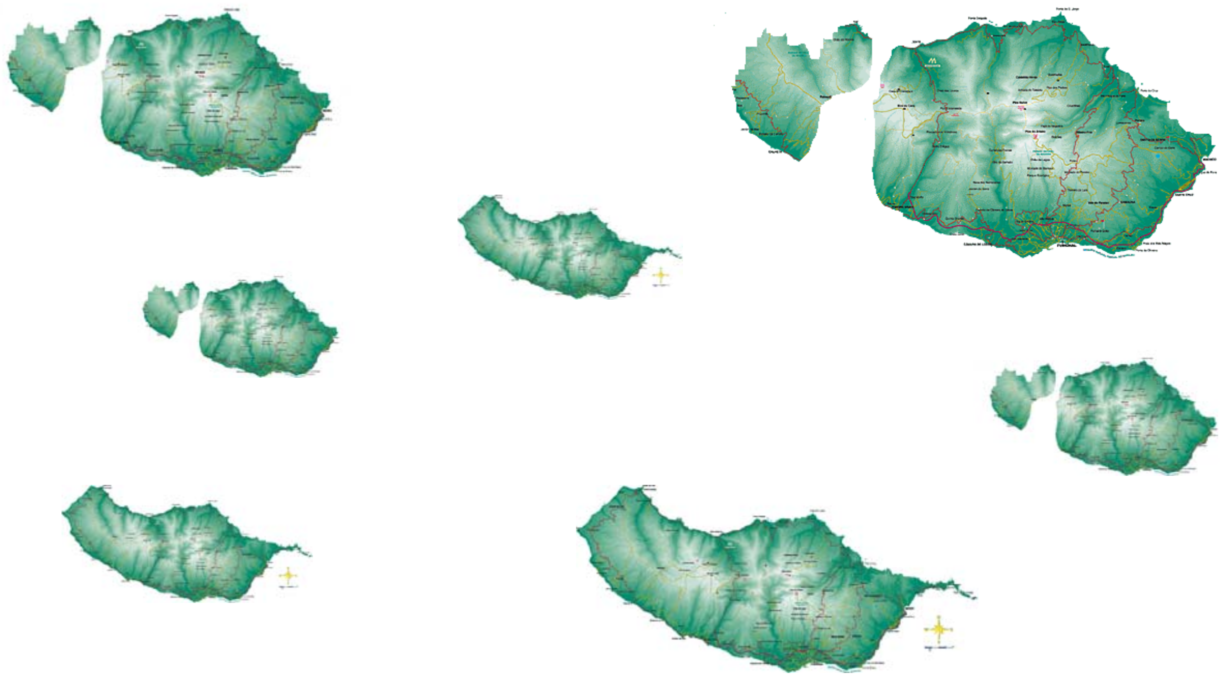
(1999)

TU Eindhoven

Philips

TU/e

Isles of Academia



...

in theory

there is no difference between theory and practice

in practice there is

…2

simulation is like masturbation:

the more you do it

the more you think it is the real thing!

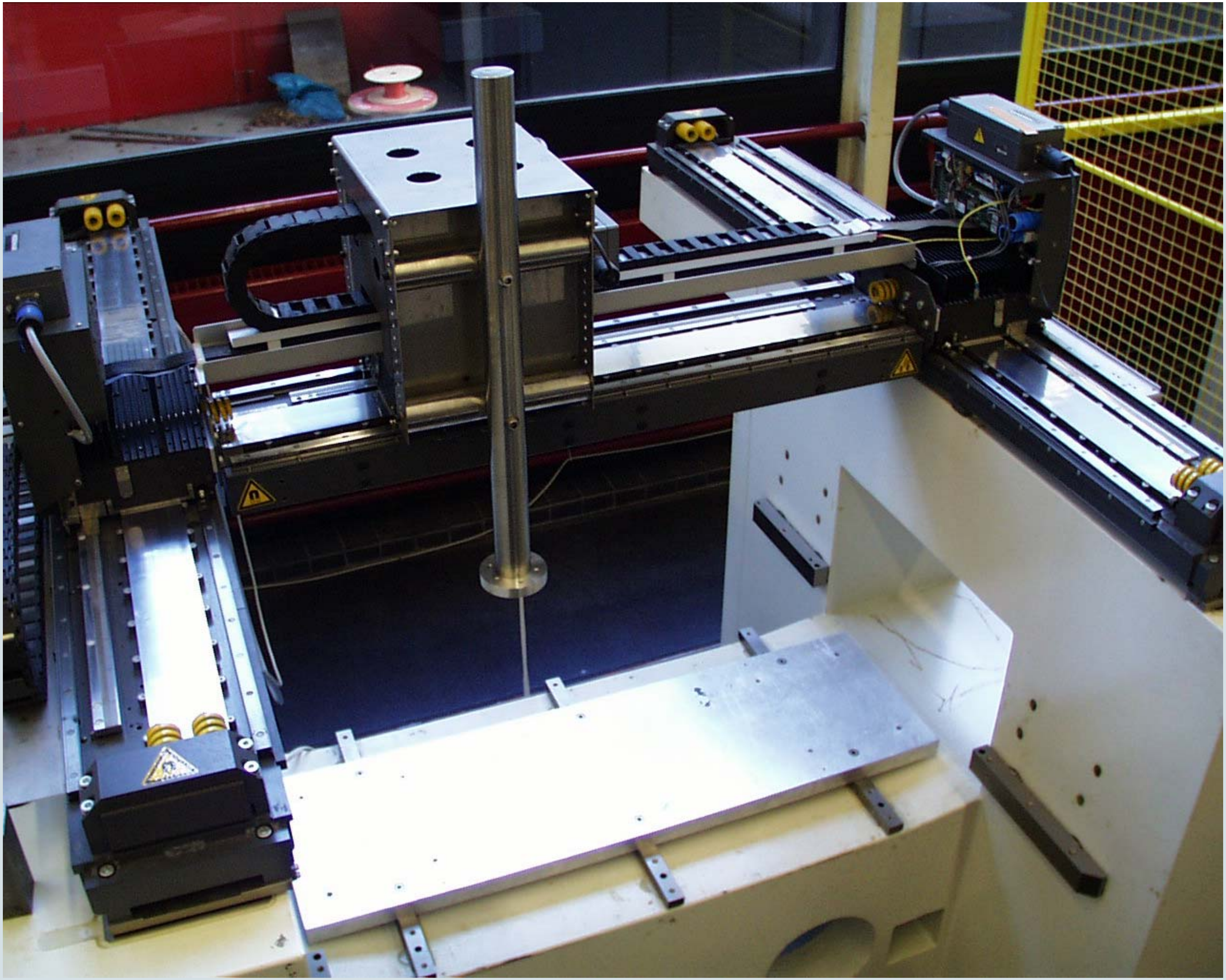
bridging the gap

- education: merge classic & modern
- bring in real industrial systems
- confront PhDs with other disciplines
- learn from experimental experience
  how to proceed with theory

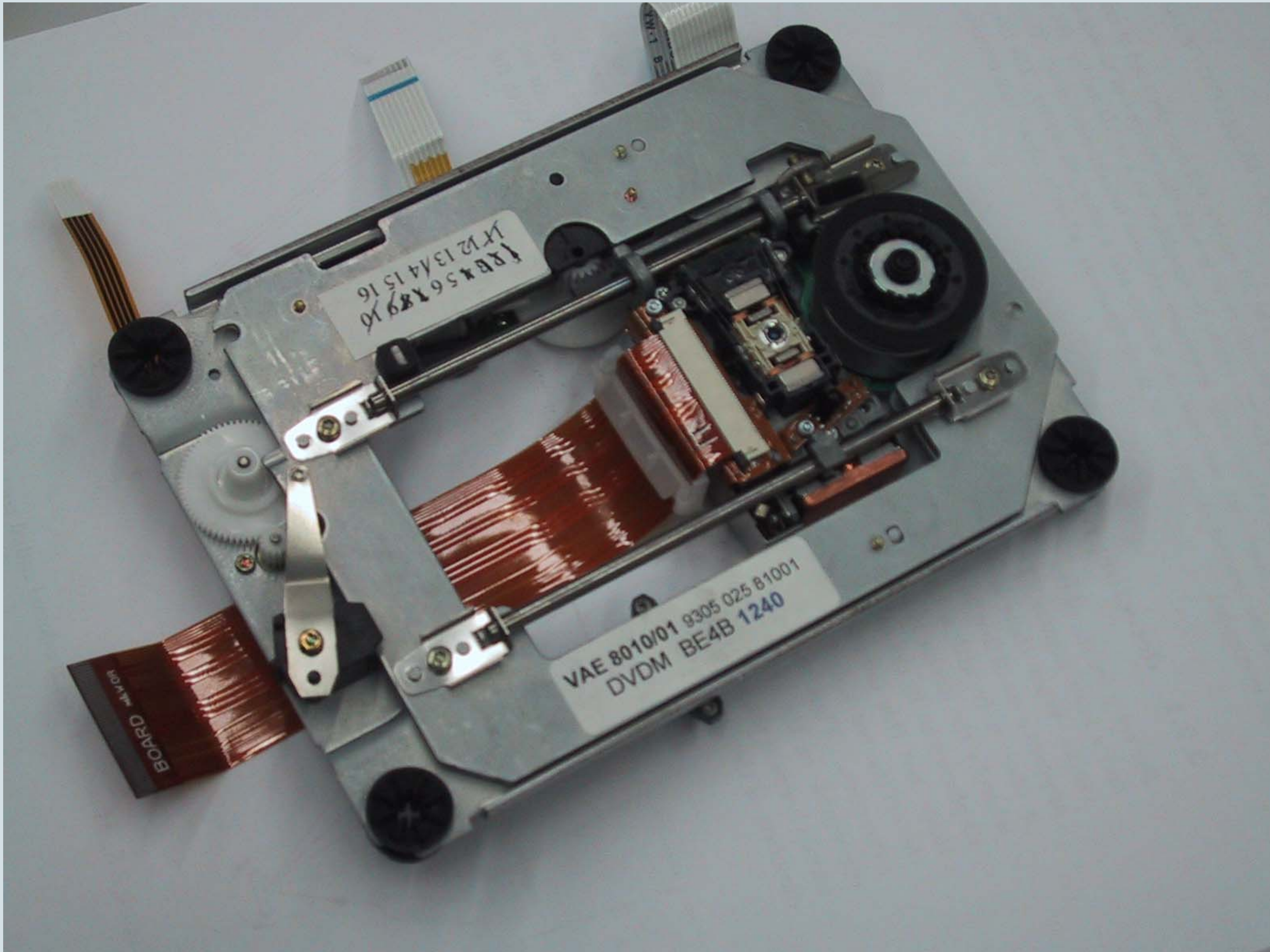
Control Systems Technology

- 1 full prof
- 2 part-time prof
- 7 associate and assistant prof
- 4 technical staff members
- 20 PhD students
- 40 MSc students/year

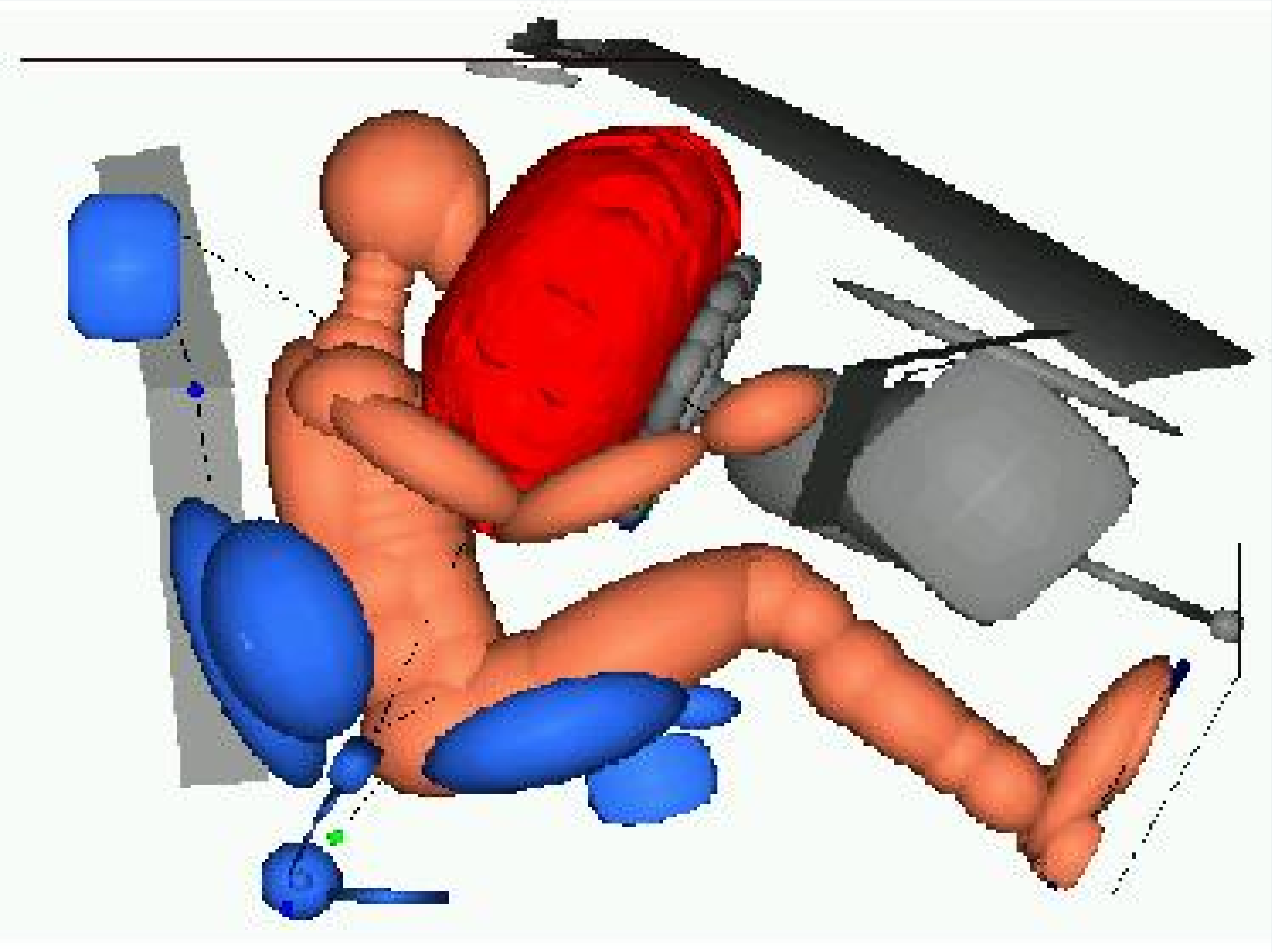
- Motion Systems
  - industrial applications (pick-and-place, (bio)-robots)
  - consumer applications (storage systems)
  - hydraulic servo systems
- Automotive
  - power trains (in particular CVT)
  - (passive) car safety systems
  - vehicle electrical power management



DaVinci surgery robot © Intuitive Surgery Inc.

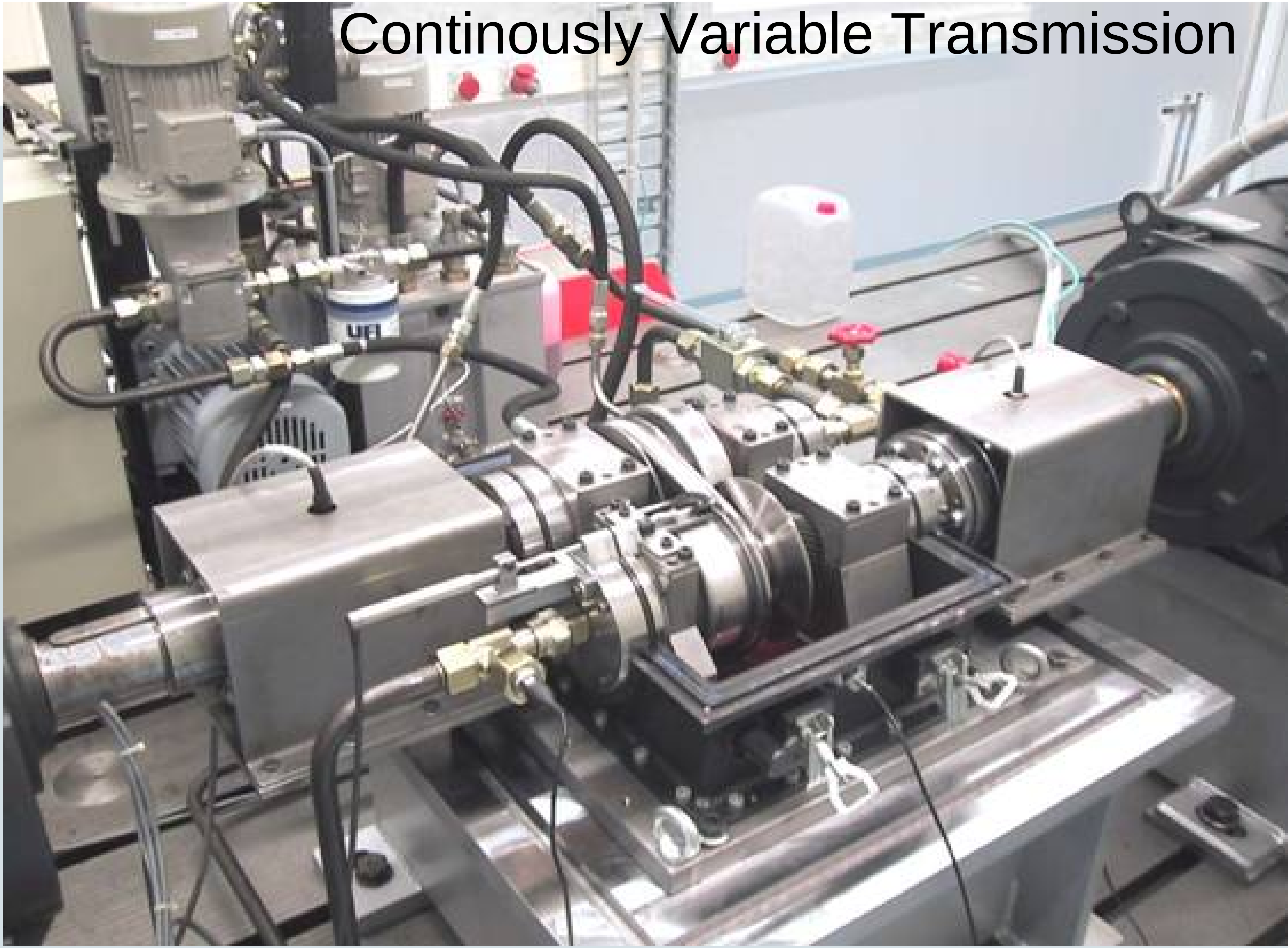

VAE 8010/01 9305 025 81001
DVDM BE4B 1240
BOARD

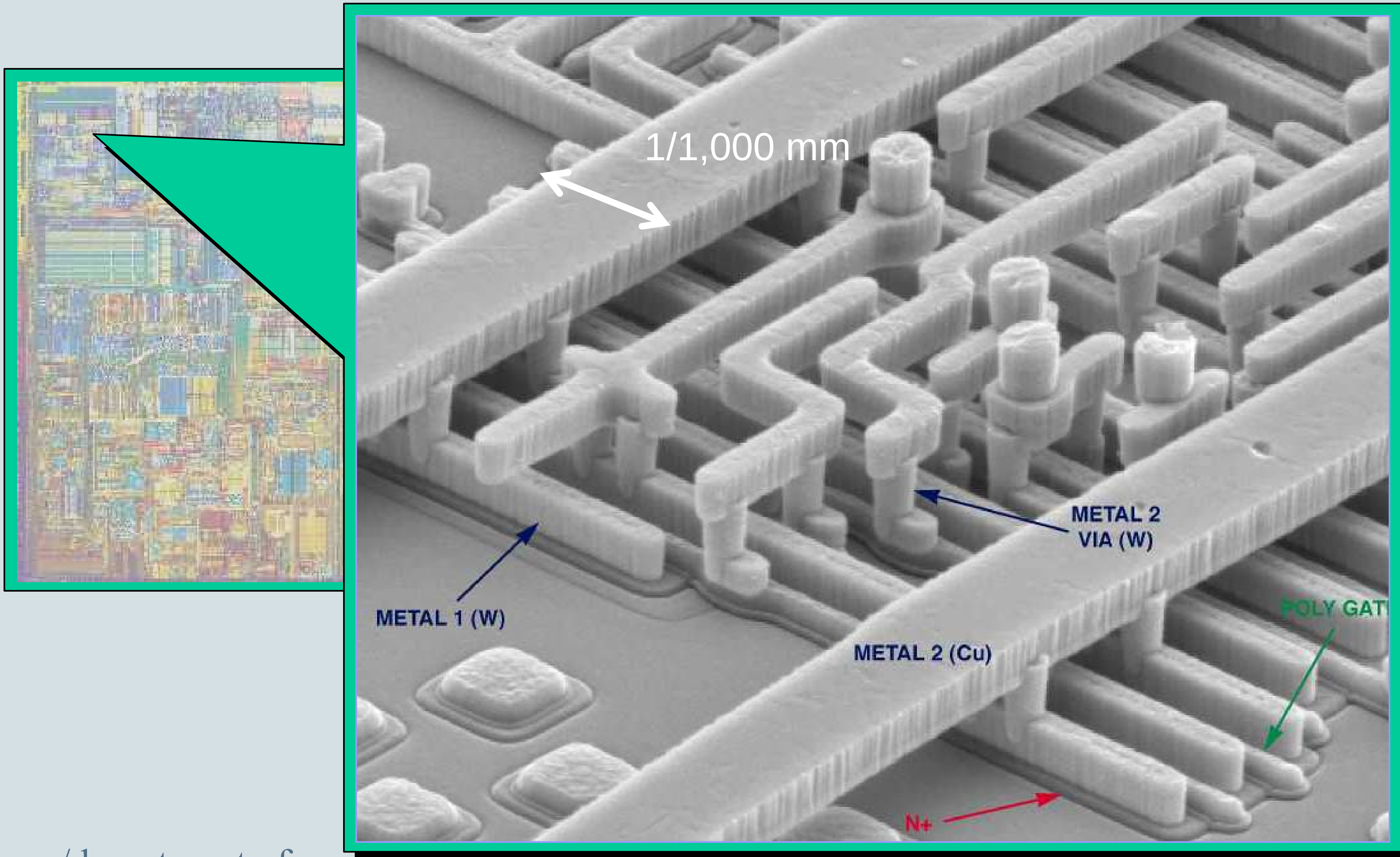
Automotive Safety Restraint Systems



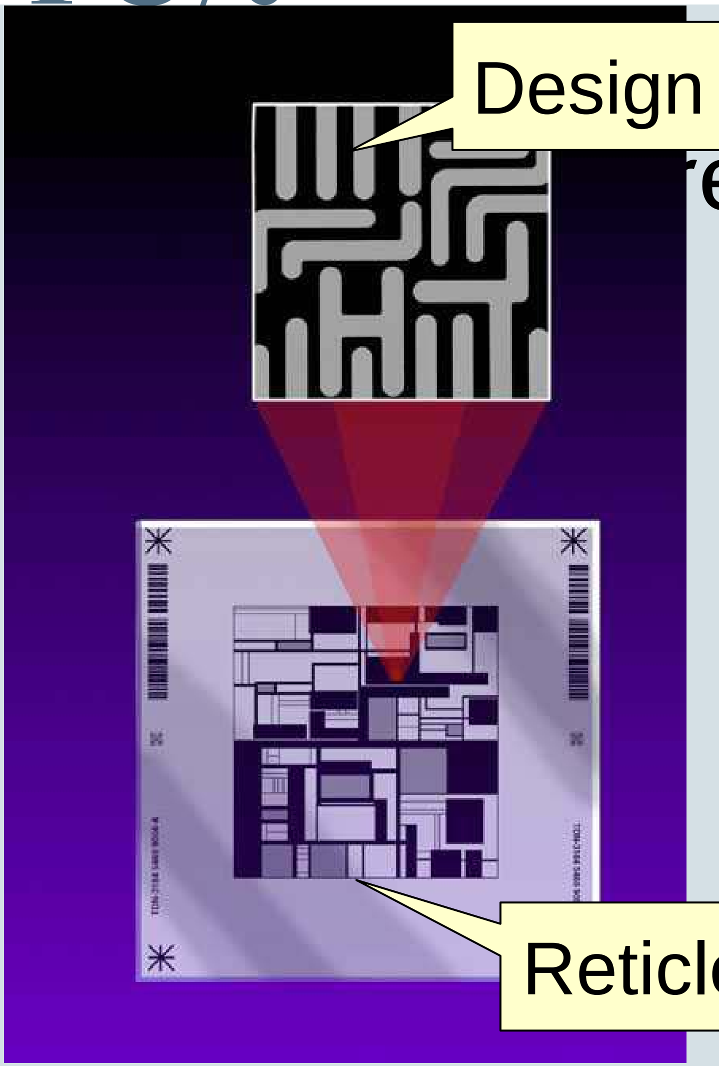
Zero-Inertia

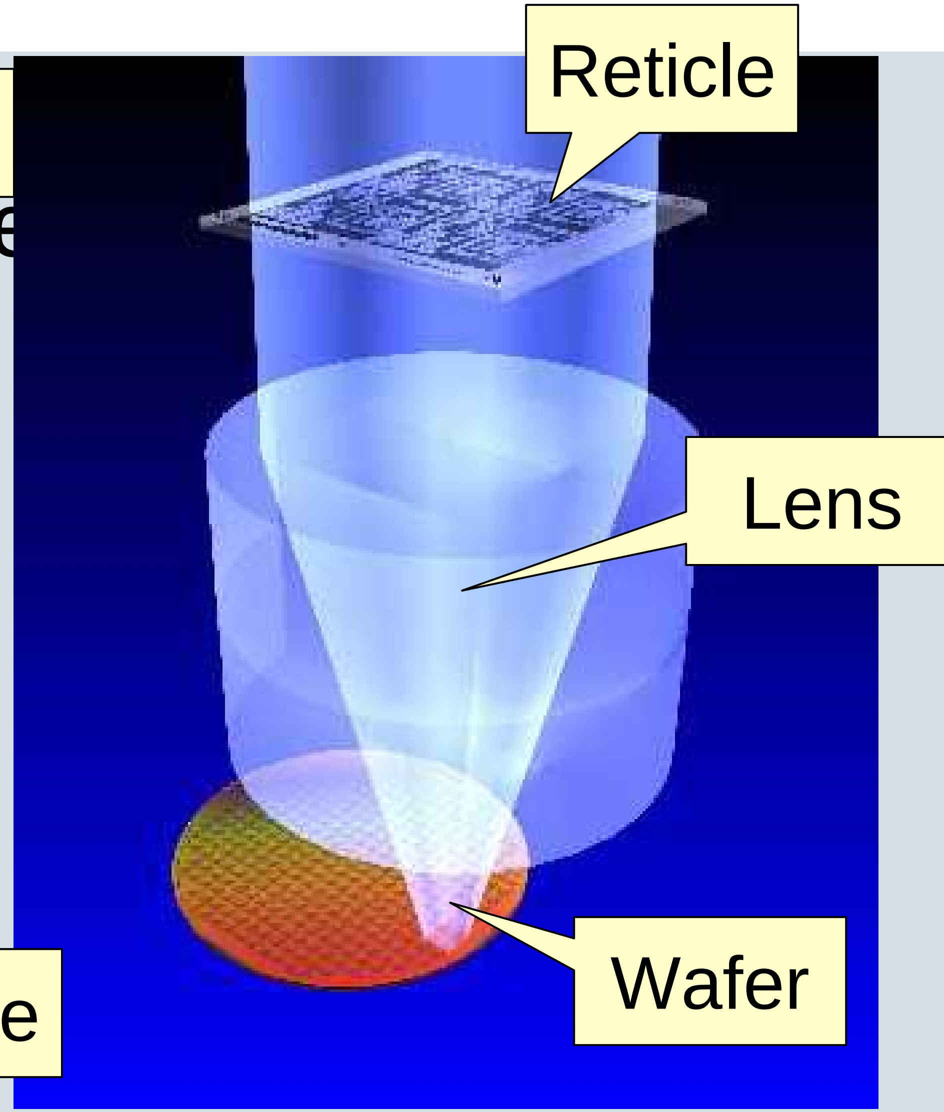
Continously Variable Transmission



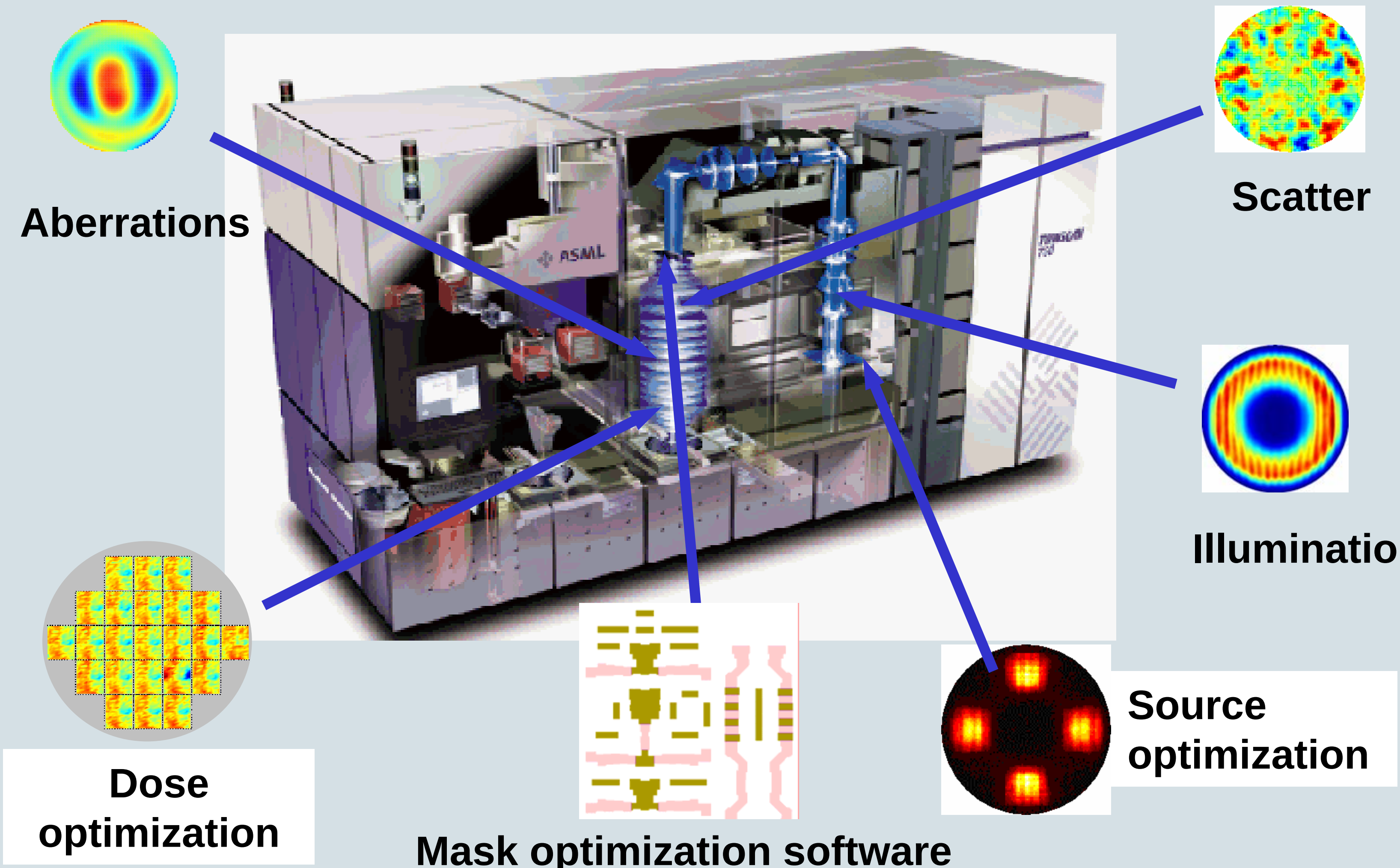


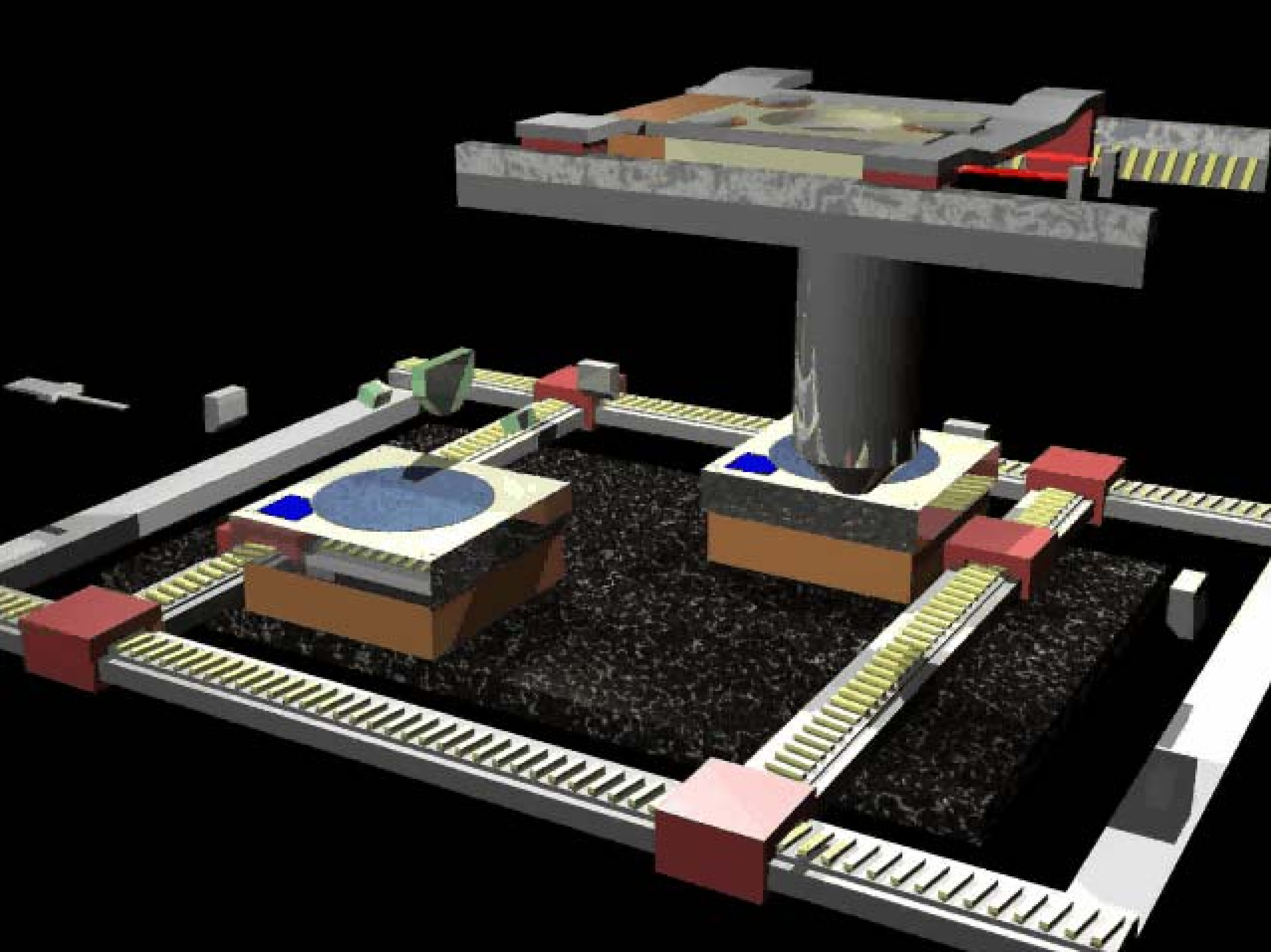
Source: intel, ICE



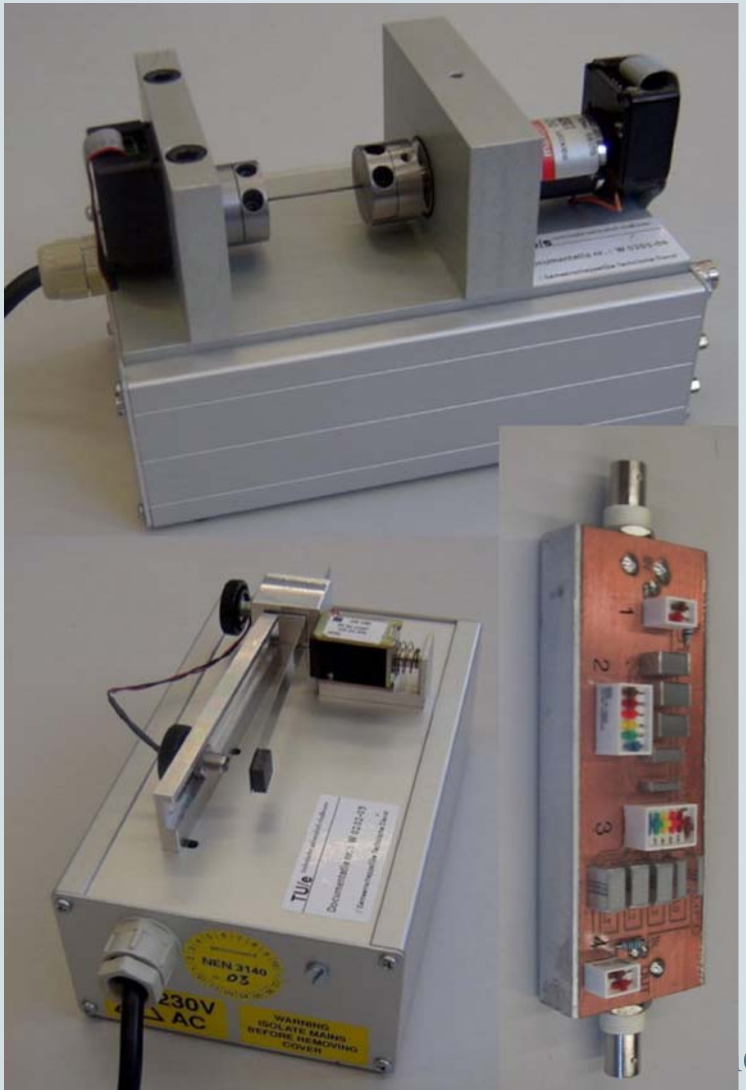


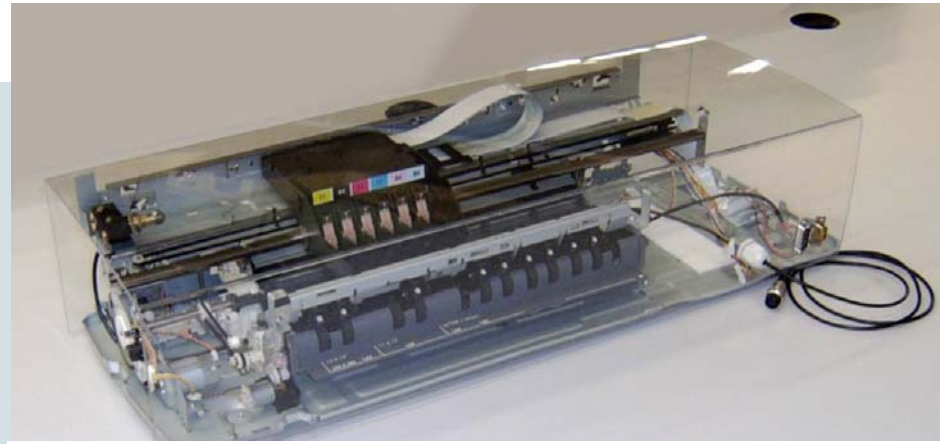
Source: ASML

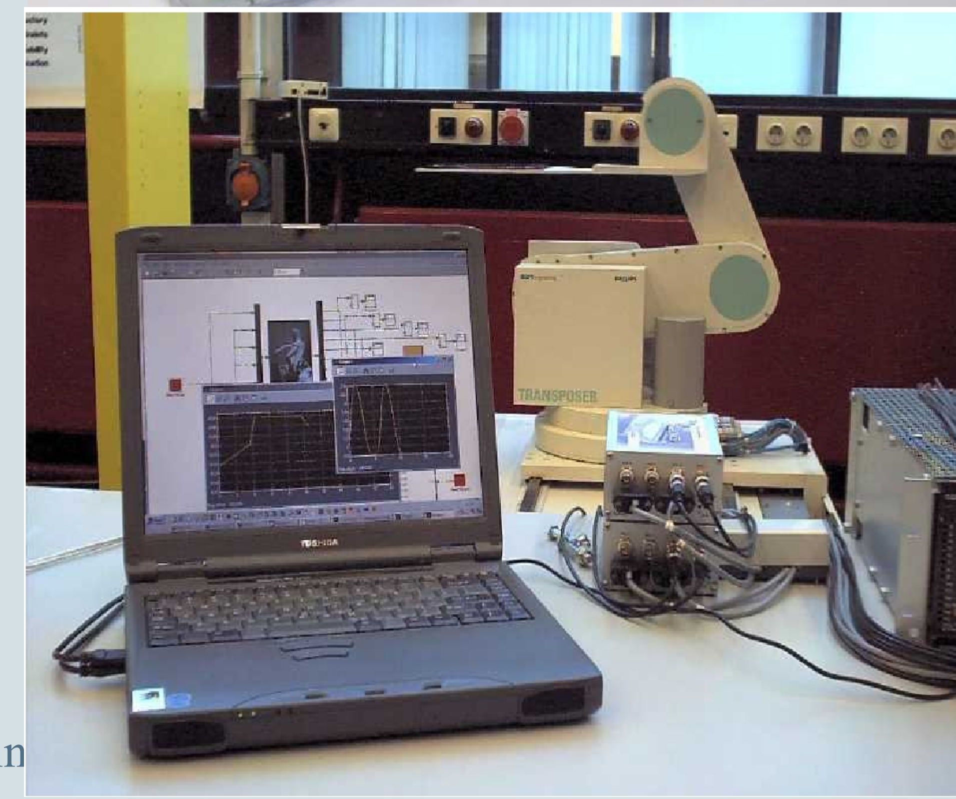

Aberrations
Scatter
Illumination
Dose optimization
Mask optimization software
Source optimization

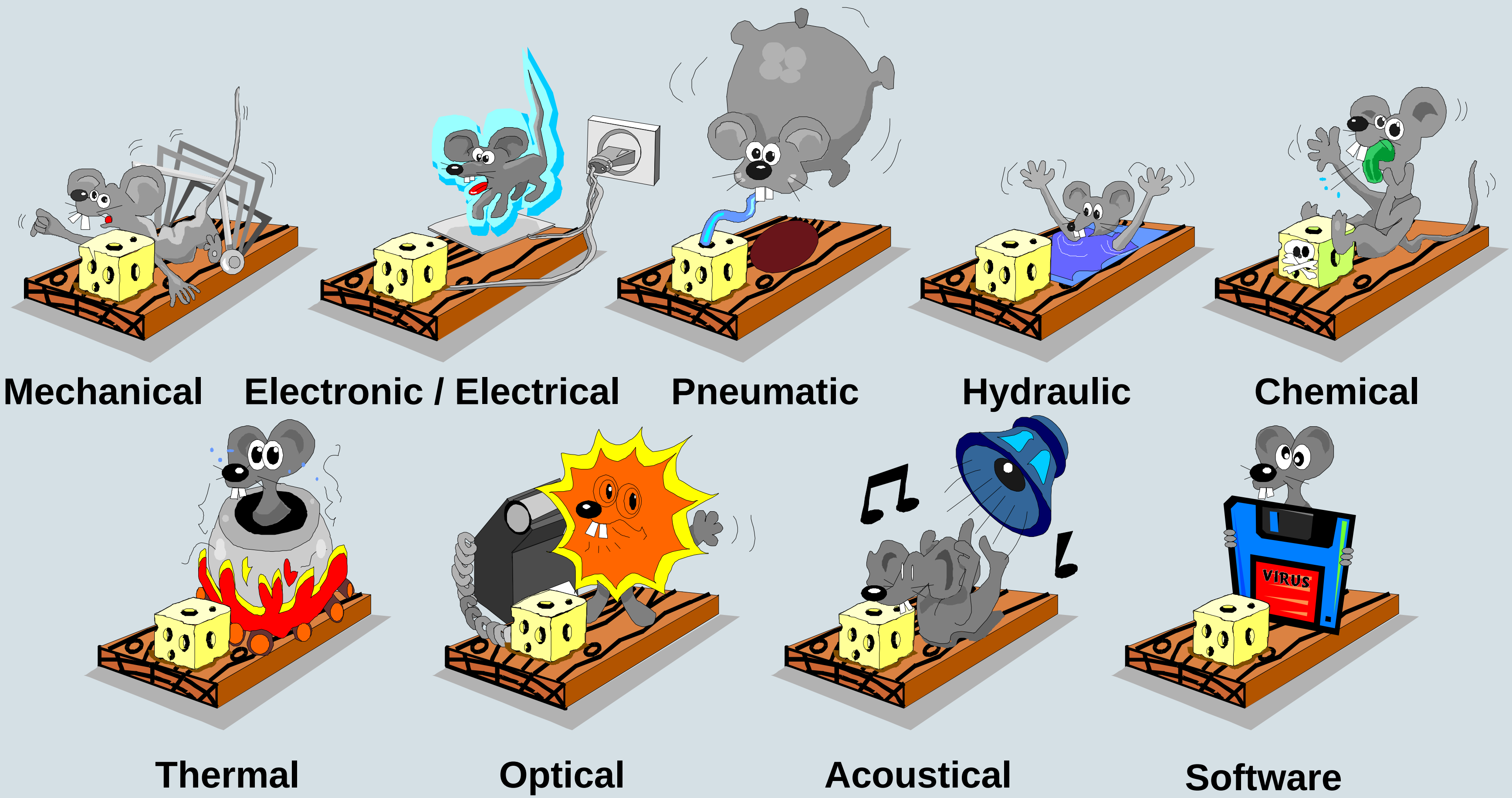


TU/e

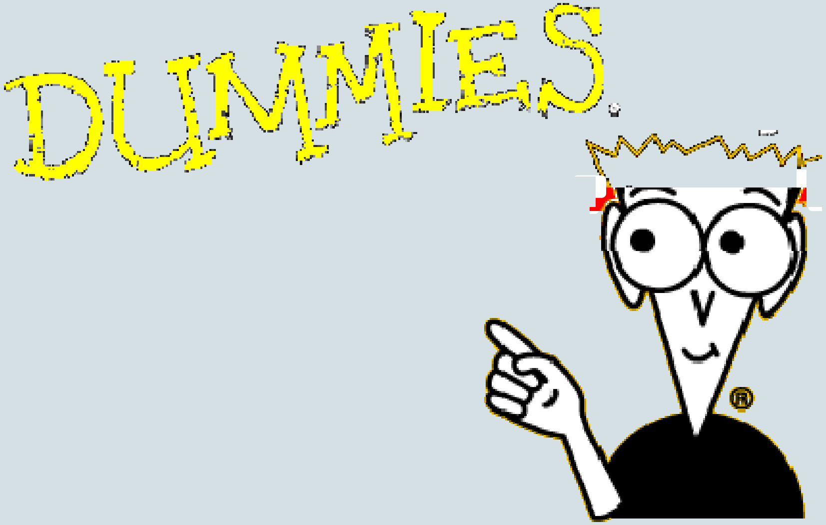

NEN 3140
03
230V
AC
WARNING
ISOLATE MAINS
BEFORE REMOVING
COVER



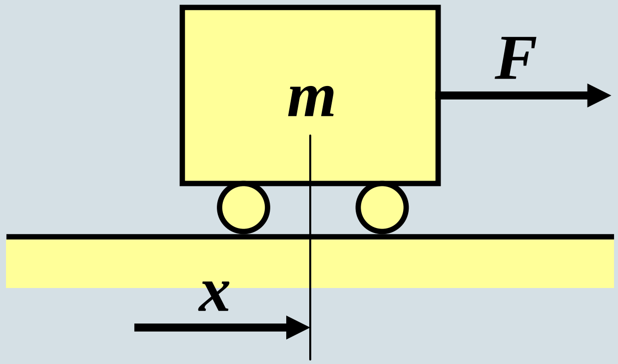

TRANSPOSER

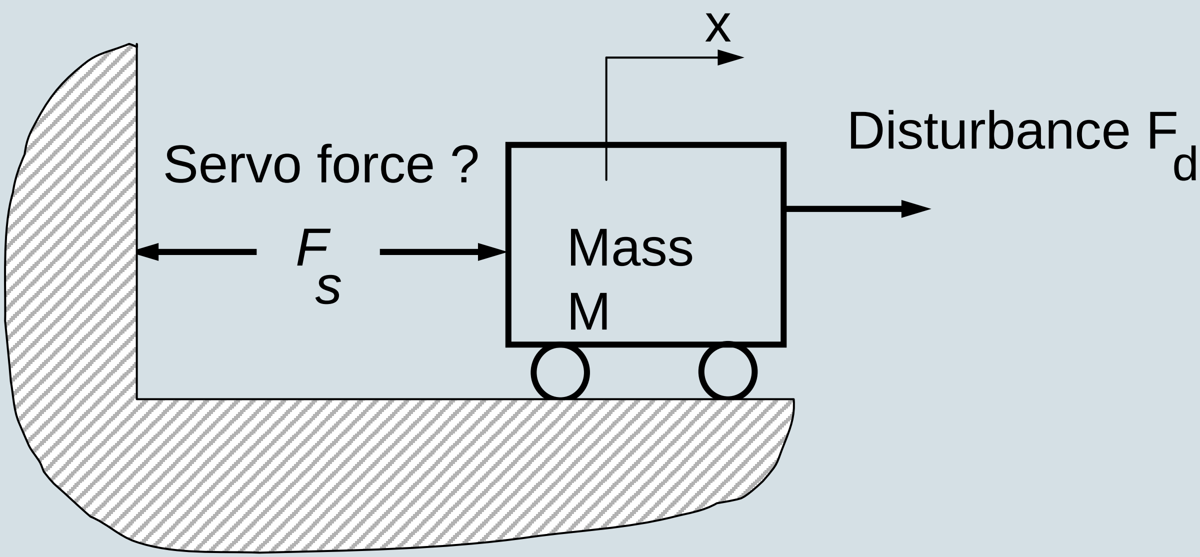

Mechanical
Electronic / Electrical
Pneumatic
Hydraulic
Chemical
Thermal
Optical
Acoustical
Software
VIRUS

Motion Control for

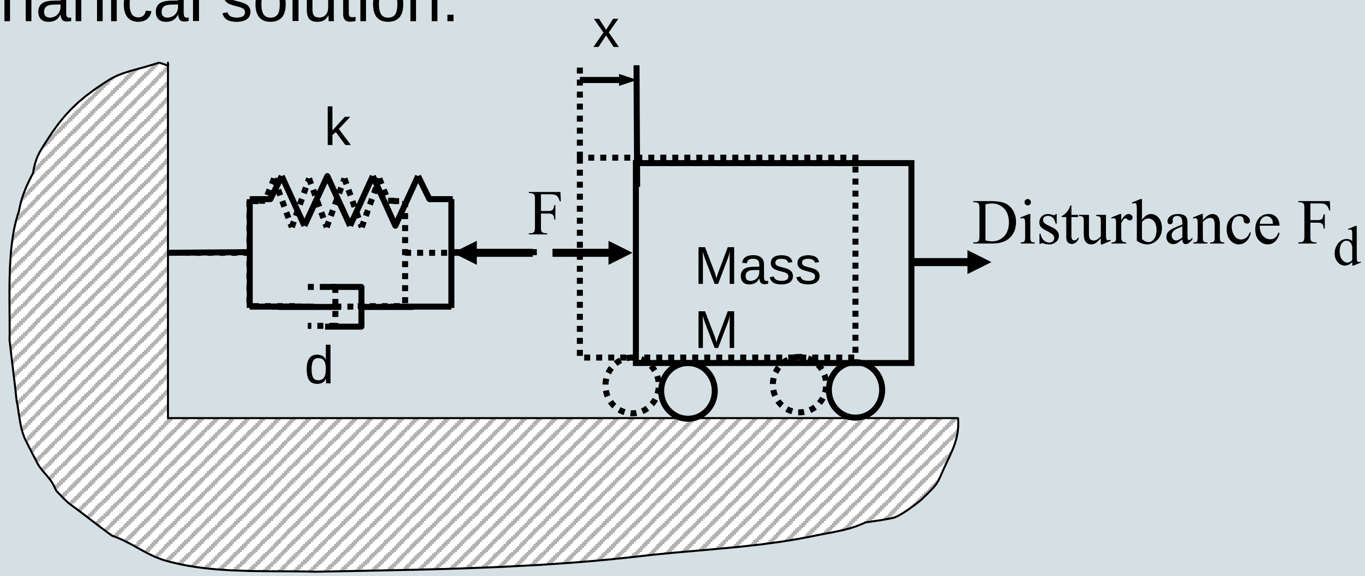


Motion Systems




x
Disturbance F
d
Servo force ?
F
s
Mass
M

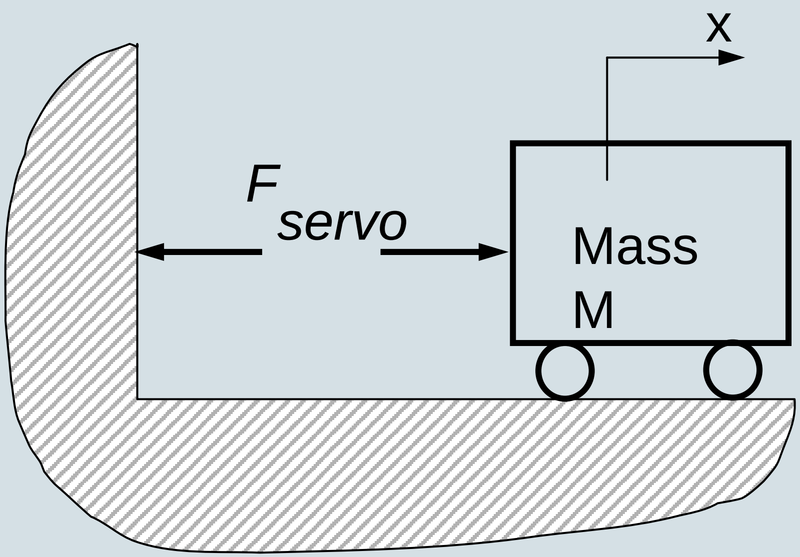
Mechanical solution:



Force spring damper $F = -k \cdot x - d \cdot \dot{x}$

Eigenfrequency $f = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$

Servo analogon:



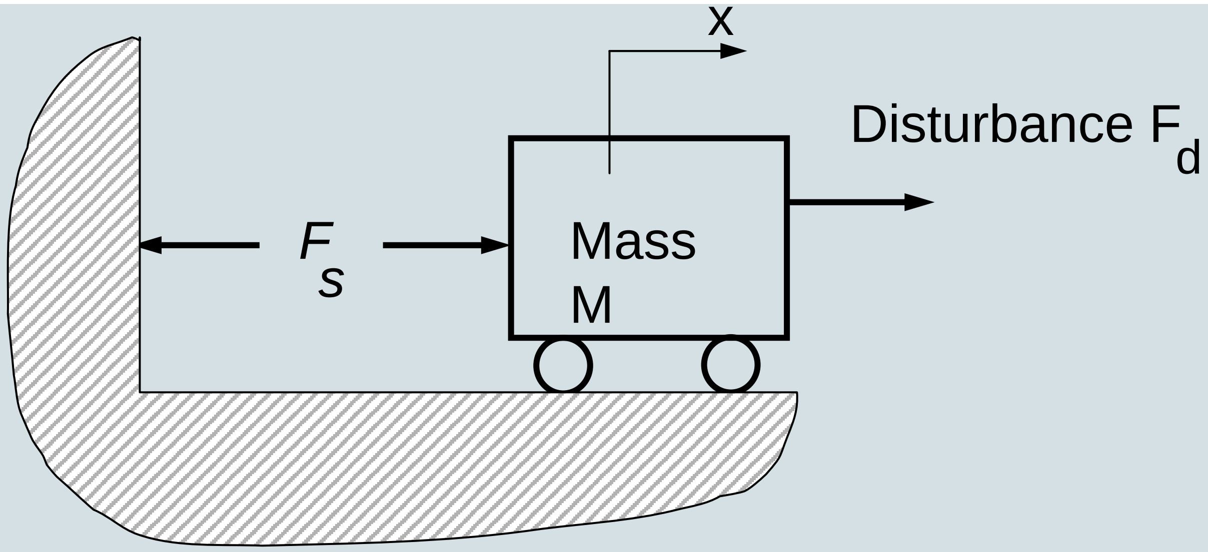
Servo force $F_s = -k_p \cdot x - k_v \cdot \dot{x}$

Eigenfrequency $f = \frac{1}{2\pi}\sqrt{\frac{k_p}{M}}$

k_p : servo stiffness

k_v : servo damping

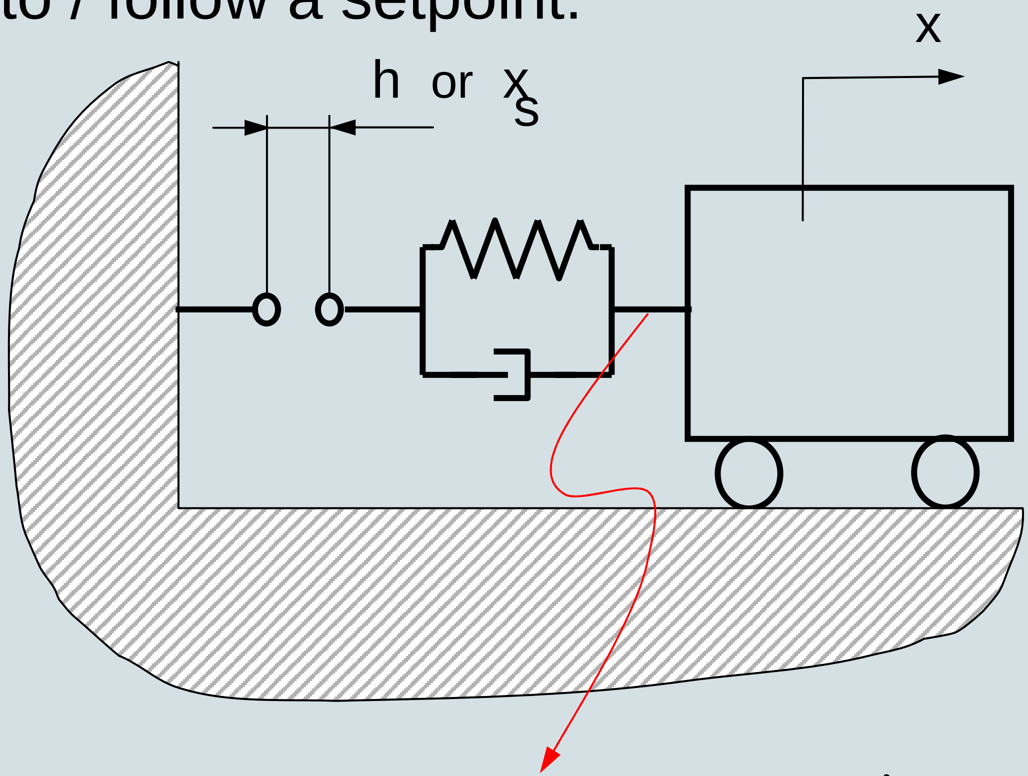
Example:



Slide: mass = 5 kg
Required accuracy 10 μm at all times
Disturbance (f.e. friction) = 3 N

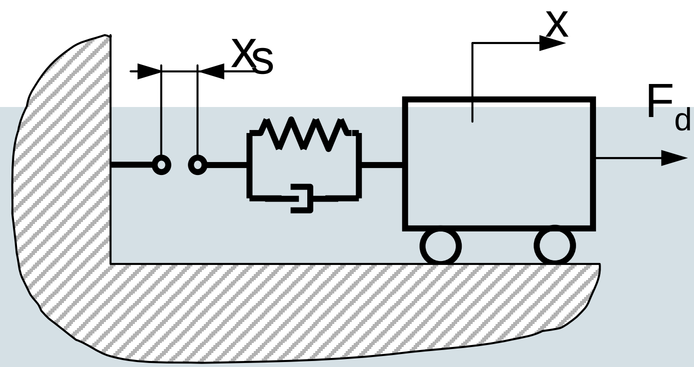
1. Required servo stiffness?
2. Eigenfrequency?

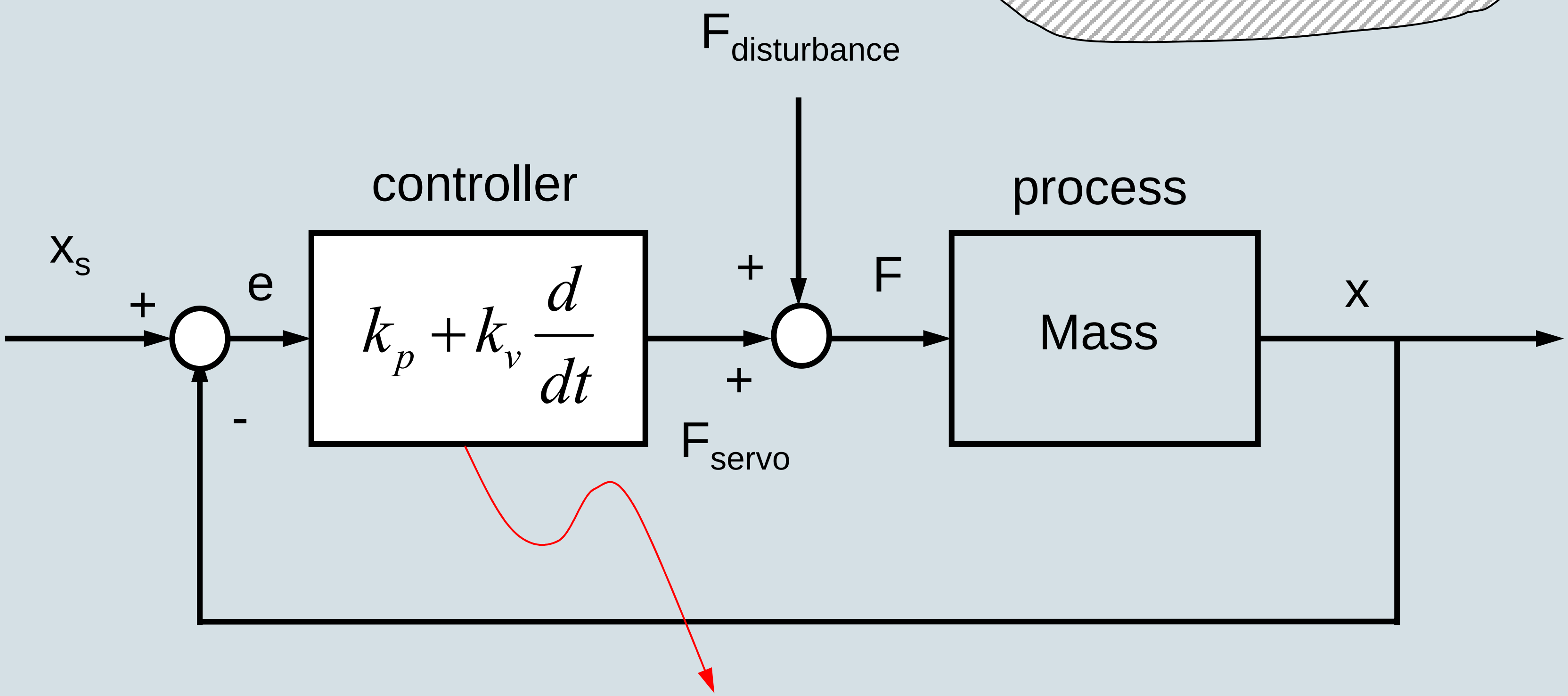
How to move to / follow a setpoint:



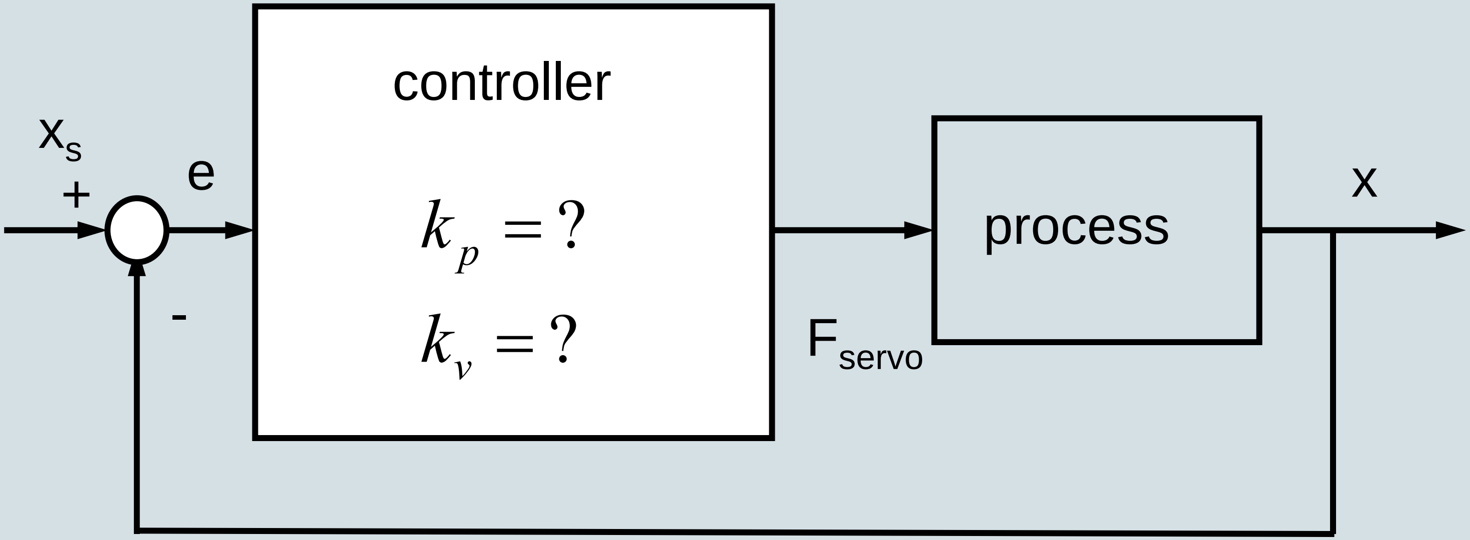
Spring-damper: $F = k(h - x) + d(\dot{h} - \dot{x})$

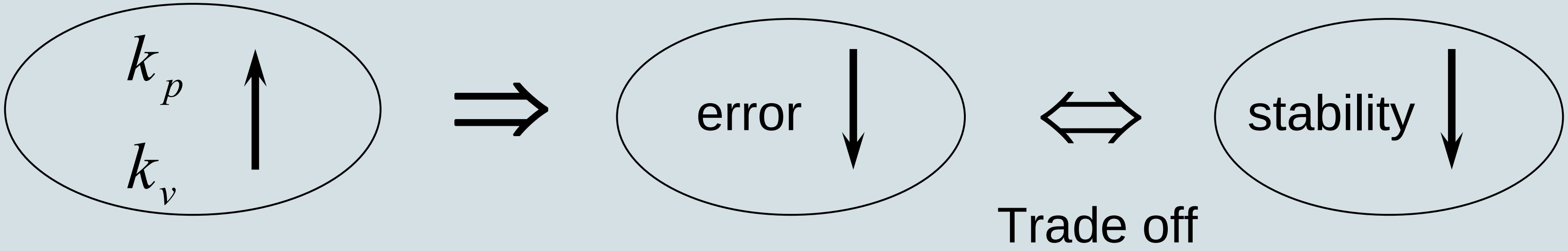
Controller $F_s = k_p(x_s - x) + k_v(\dot{x}_s - \dot{x})$



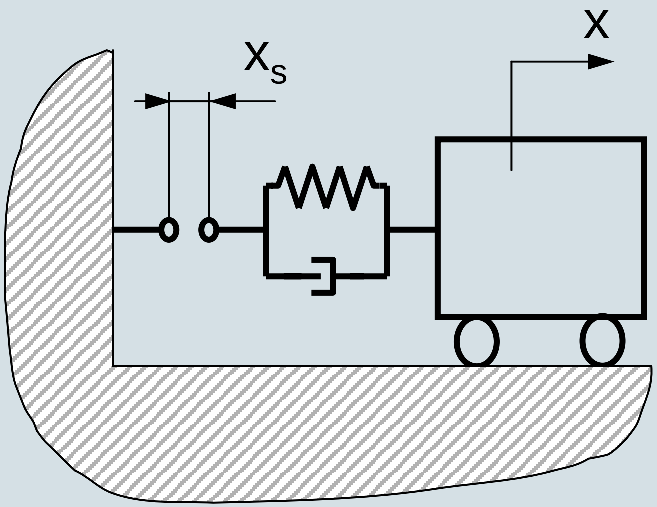


K_p/k_v-controller or PD-controller


controller
$k_p = ?$
$k_v = ?$
x_s
+
-
e
F_{servo}
process
x


k_p
k_v
⇒
error
⇔
stability
Trade off

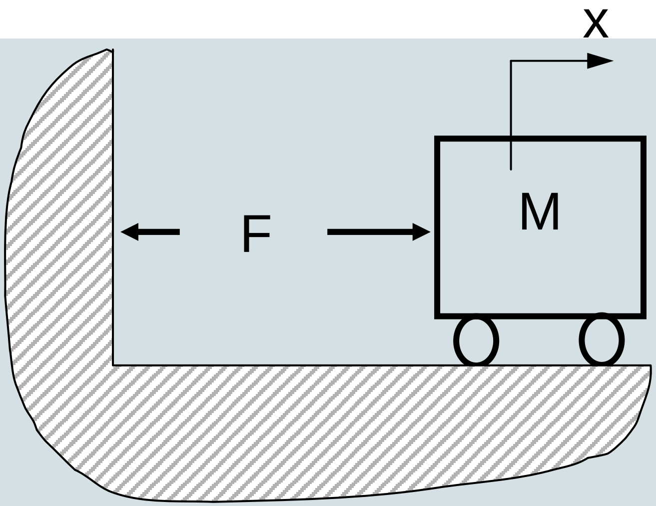
Setpoints:



What should x_s look like as a function of time, when moving the mass?

(first order, second order, third order,….?)

Apply a force *F* (step profile):



$$F(t) = M\ddot{x}(t)$$

$$\Downarrow$$

x(t) is second order, when *F* constant

Second order profile requires following information:

- maximum acceleration
- maximum velocity
- travel distance

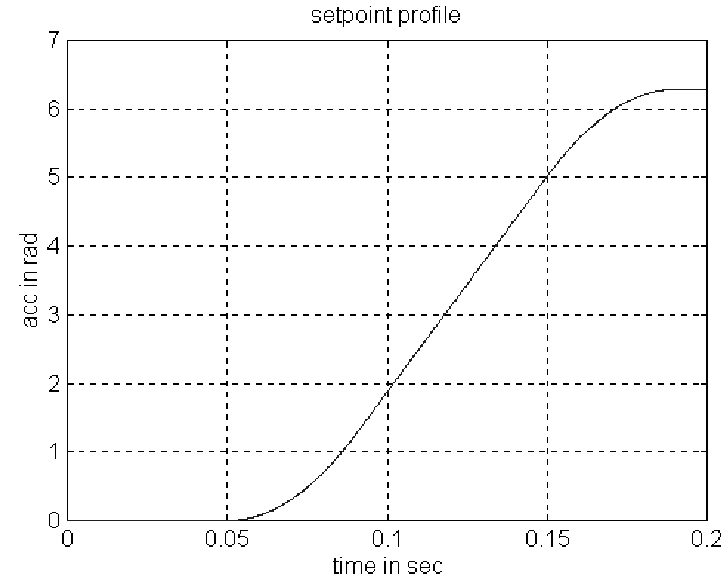
Example

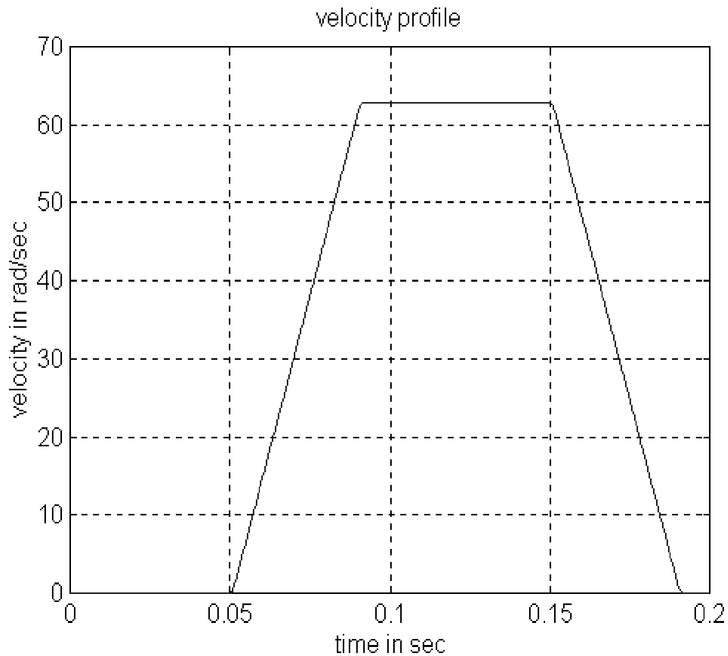
TU/e

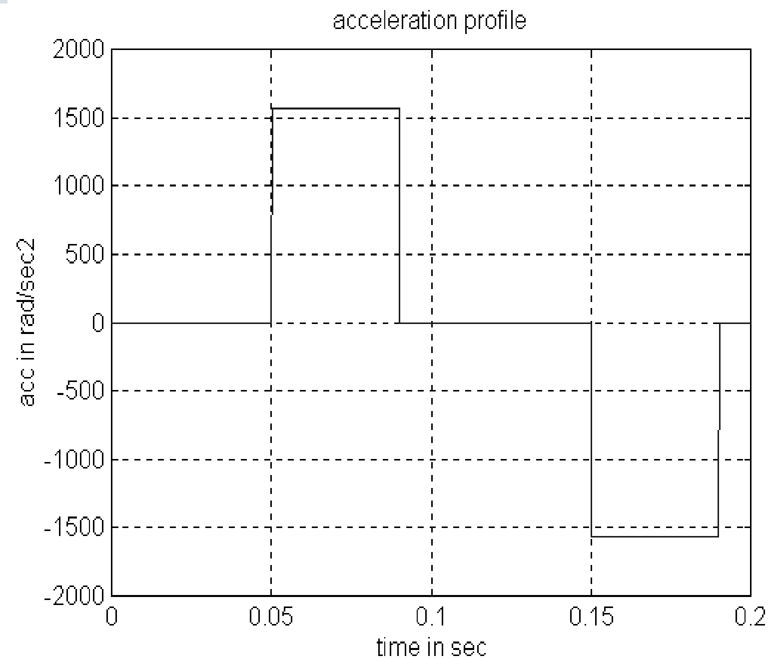
$$Pos = 2\pi \approx 6.3 rad$$

$$Vel_{max} = 20\pi \approx 63 rad / \sec$$

$$Acc_{max} = 500\pi \approx 1.6e3 rad / \sec^2$$



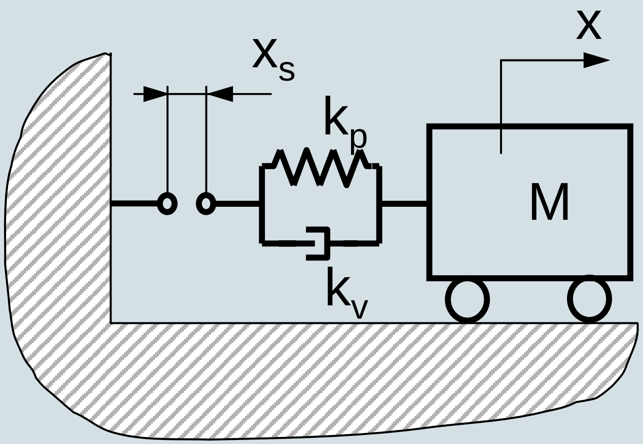




Concluding remarks time domain tuning

A control system, consisting of only a single mass m and a k_p/k_v controller (as depicted below), is *always* stable.
k_p will act as a spring; k_v will act as a damper

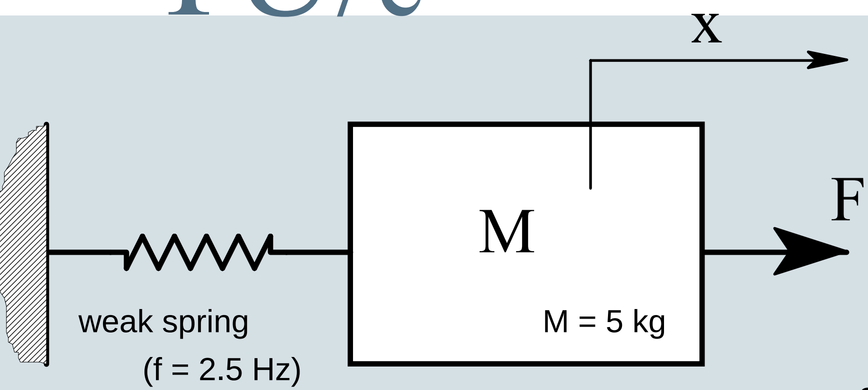
As a result of this: when a control system is unstable, it *cannot* be a pure single mass + k_p/k_v controller
(With positive parameters m, k_p and k_v)



Frequency domain

Time domain:
Monday and Thursday at 22:10

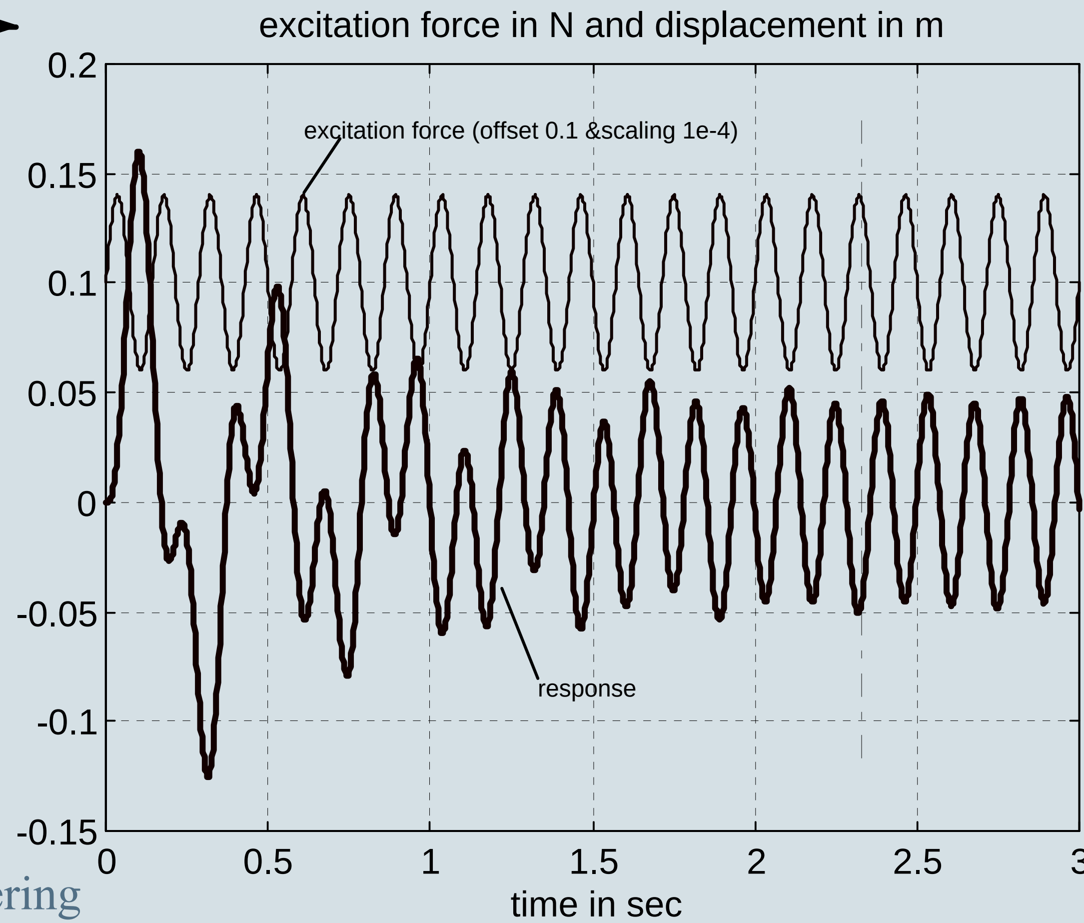
Frequency domain:
twice a week



$$F(t) = 400\sin(2\pi 7t)$$

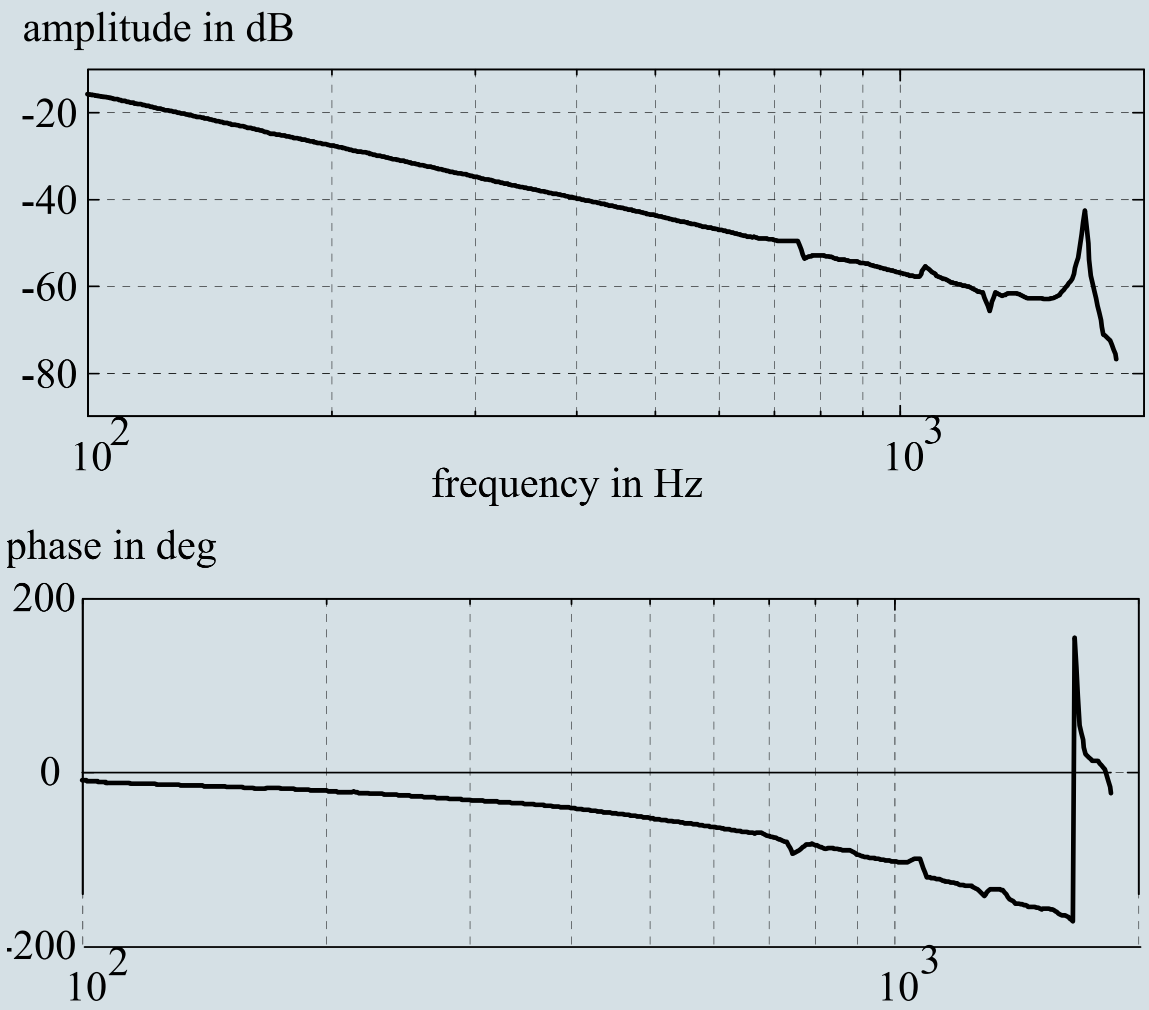
$$|H(7Hz)| \approx 0.045/400 = 1e-4 \ m/N$$

$$\angle H(7Hz) \approx -180^0$$



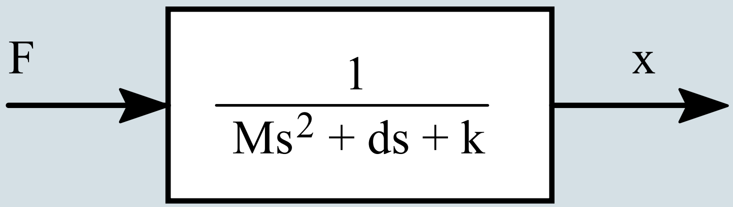
TU/e

measurement mechanics stage



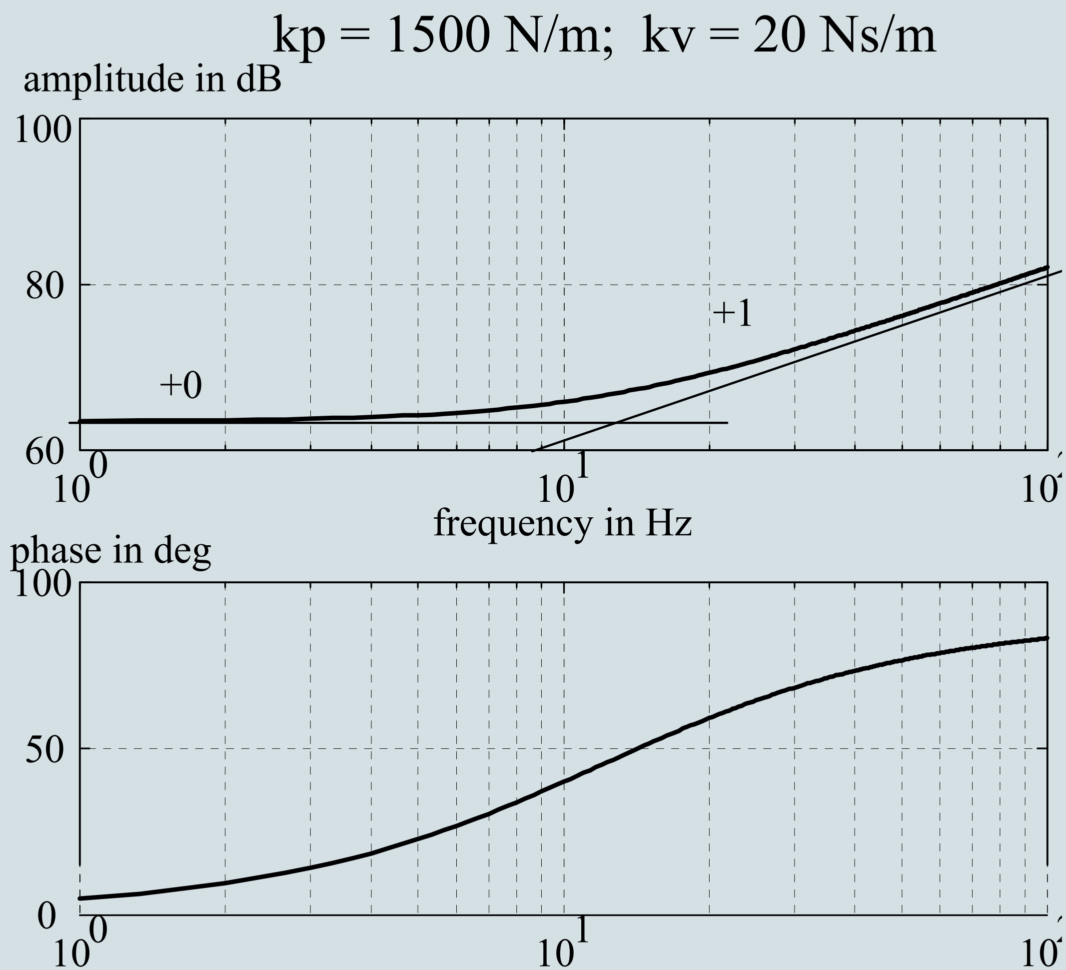
Transfer function:

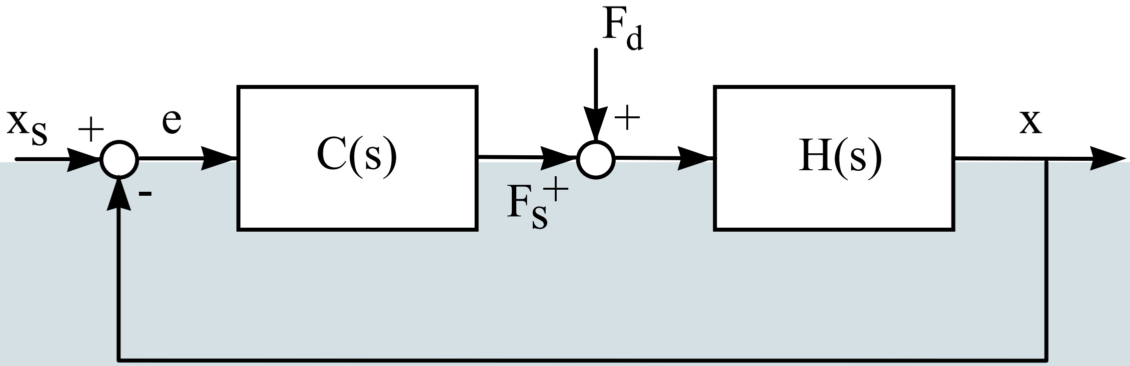
$$H(s)=\frac{x(s)}{F(s)}=\frac{1}{Ms^2+ds+k}$$



TU/e

Bode plot of the PD-controller:





Four important transfer functions

1. Open loop $$L(s) = C(s)H(s)$$

2. Closed loop $$T(s) = \frac{x}{x_s}(s) = \frac{C(s)H(s)}{1 + C(s)H(s)}$$

3. Sensitivity $$S(s) = \frac{e}{x_s}(s) = \frac{1}{1 + C(s)H(s)}$$

4. Proces Sensitivity $$H_{ps}(s) = \frac{x}{F_d}(s) = \frac{H(s)}{1 + C(s)H(s)}$$

Mimo

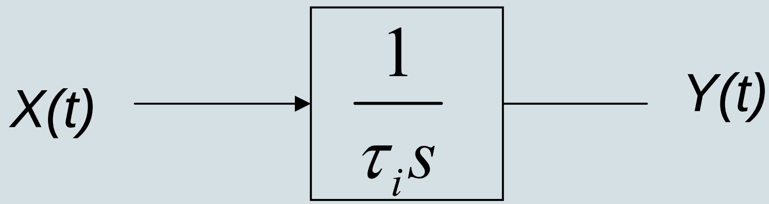
Filters

PeeDee

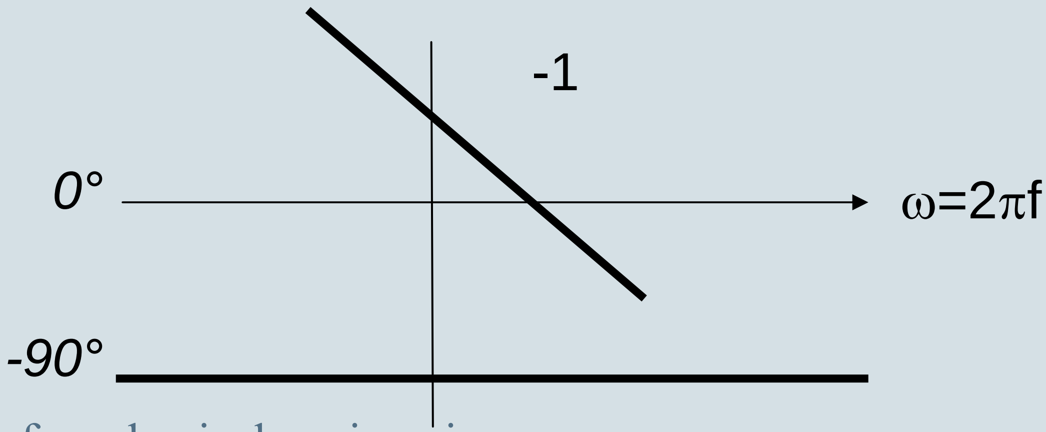
PeeEye

- Integral action
- Differential action
- Low-pass
- High-pass
- Band-pass
- Notch filter

Integral action :

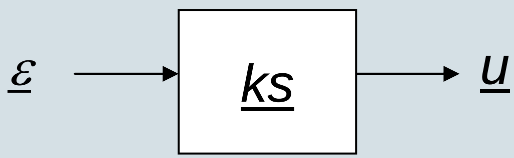


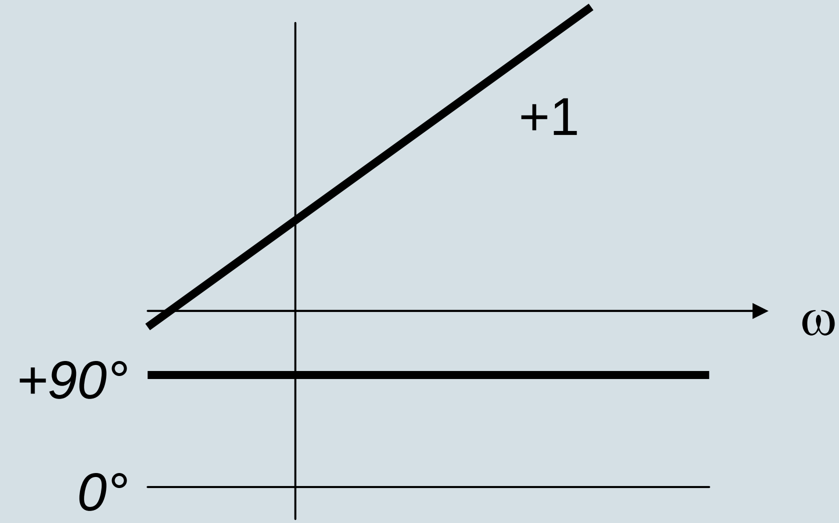
τ_I integral time constant $\tau_I = 1/k_i$



Differential action

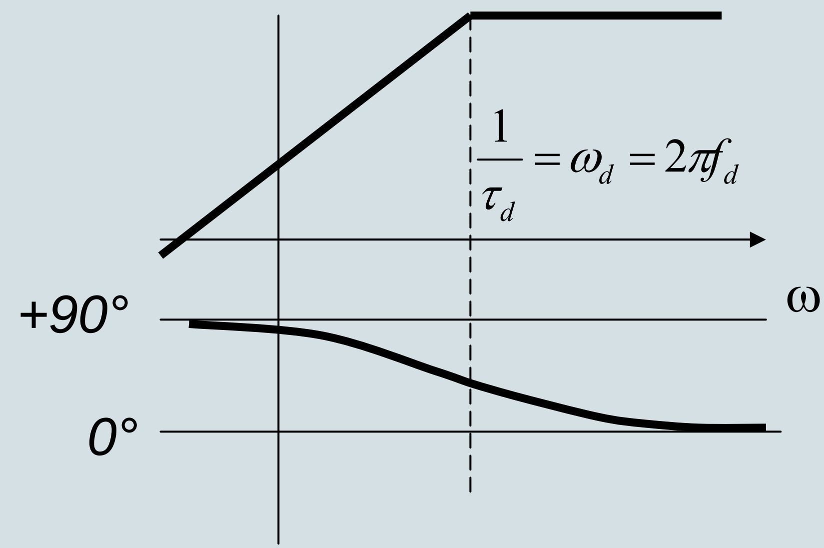
$$H = ks = \frac{u}{\varepsilon}; \quad s = j\omega; \quad \left|\frac{u}{\varepsilon}\right| = k\omega$$





"tamme" differentiator :

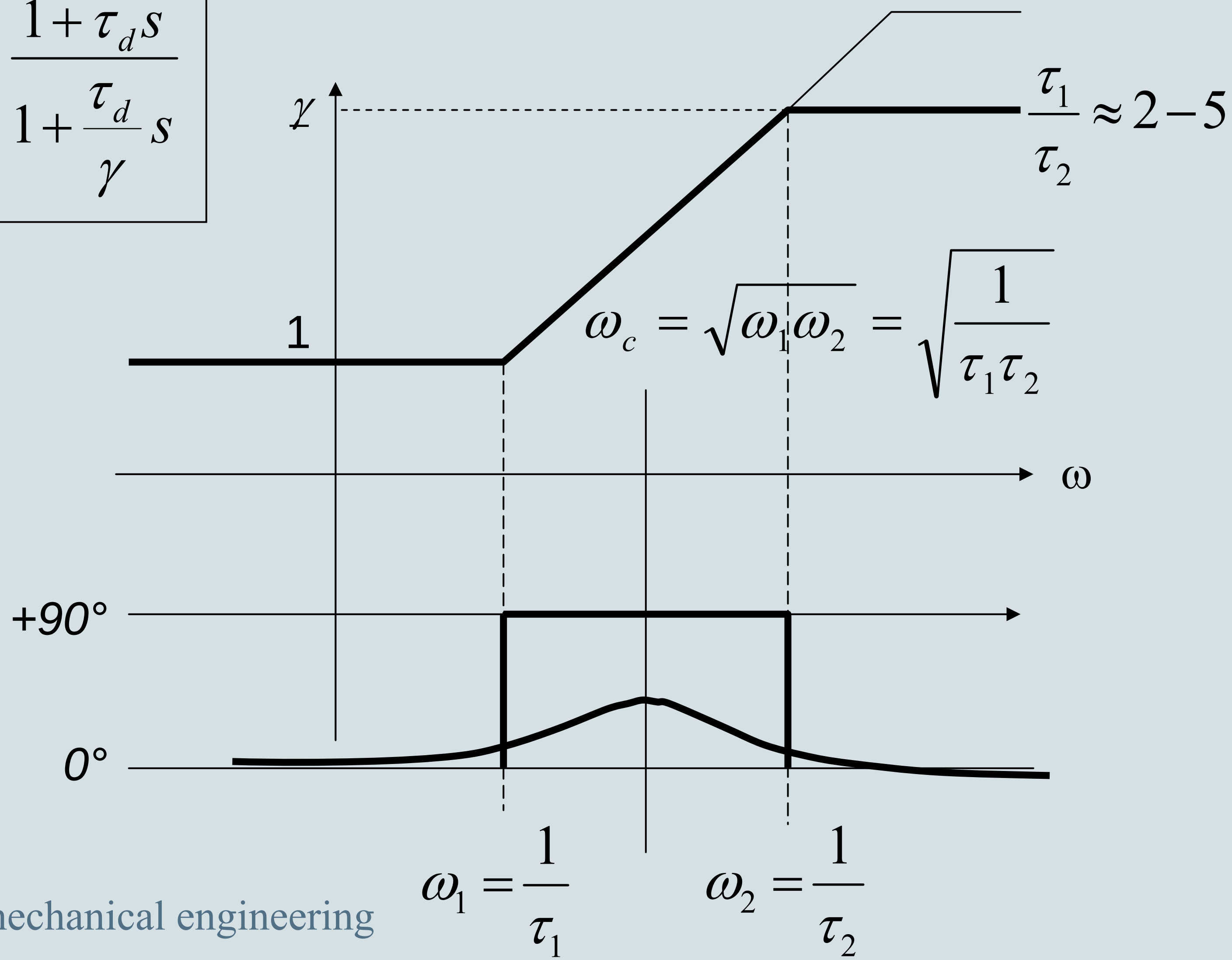
$$\frac{u}{\varepsilon} = \frac{ks}{\tau_d s + 1}$$



"lead" filter

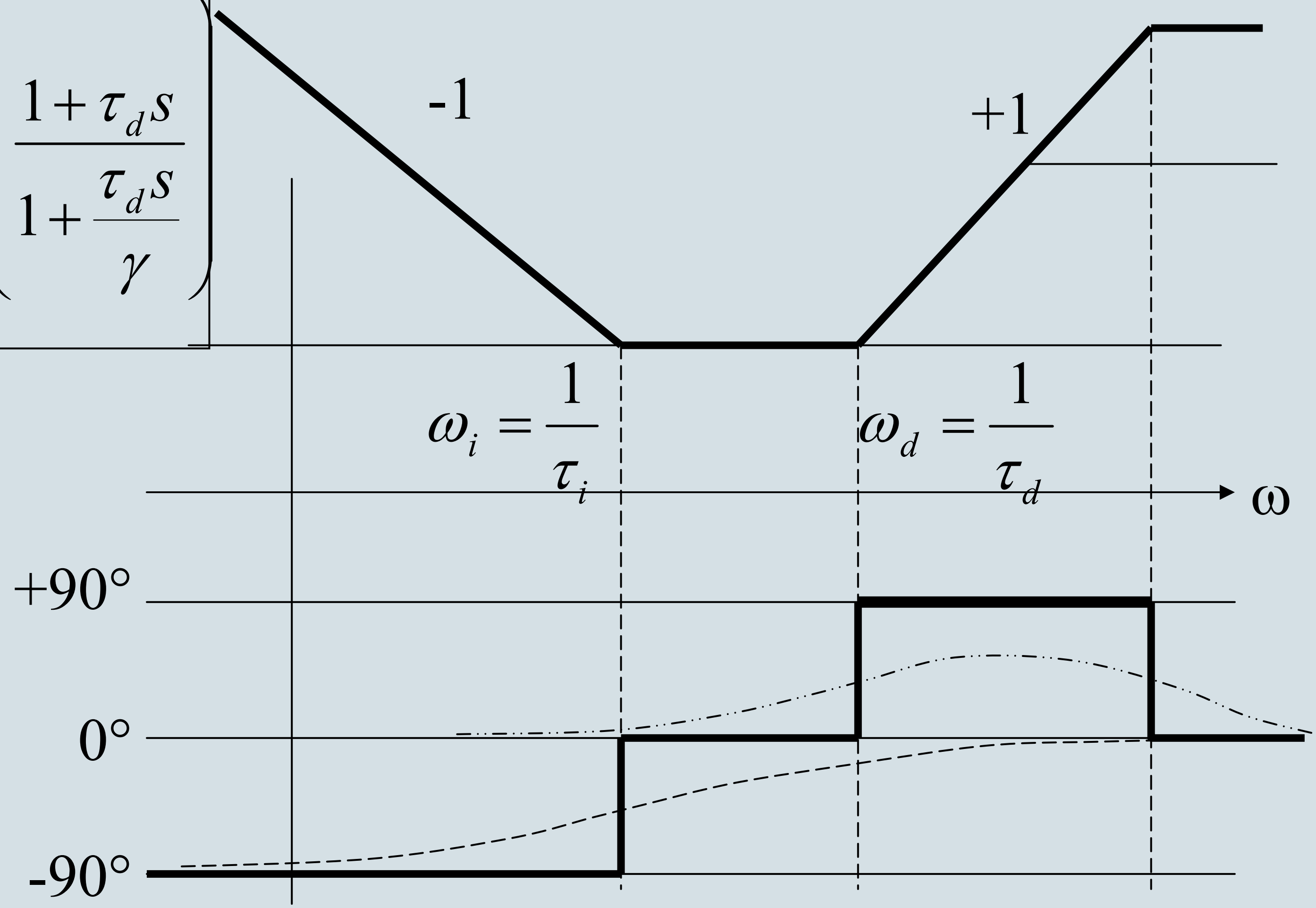
$$H = \frac{u}{\varepsilon} = \frac{1+\tau_1 s}{1+\tau_2 s} = \frac{1+\tau_d s}{1+\frac{\tau_d}{\gamma} s}$$

$\gamma > 1$



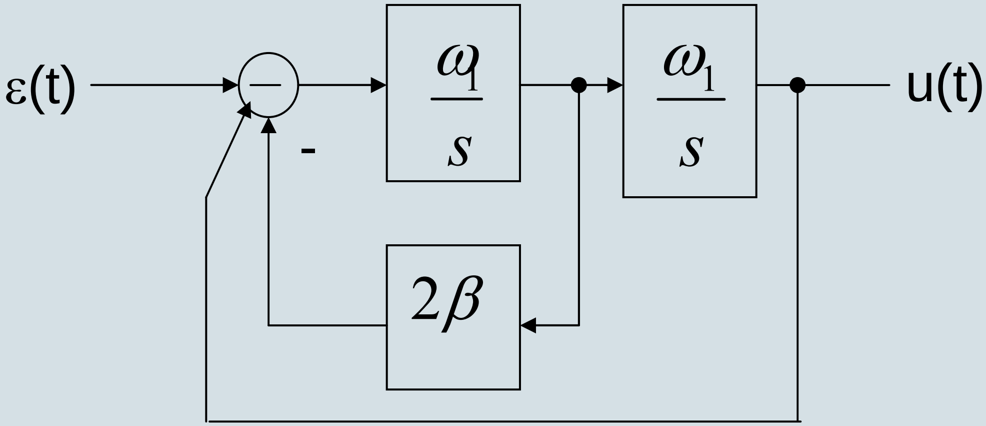
P+I+D

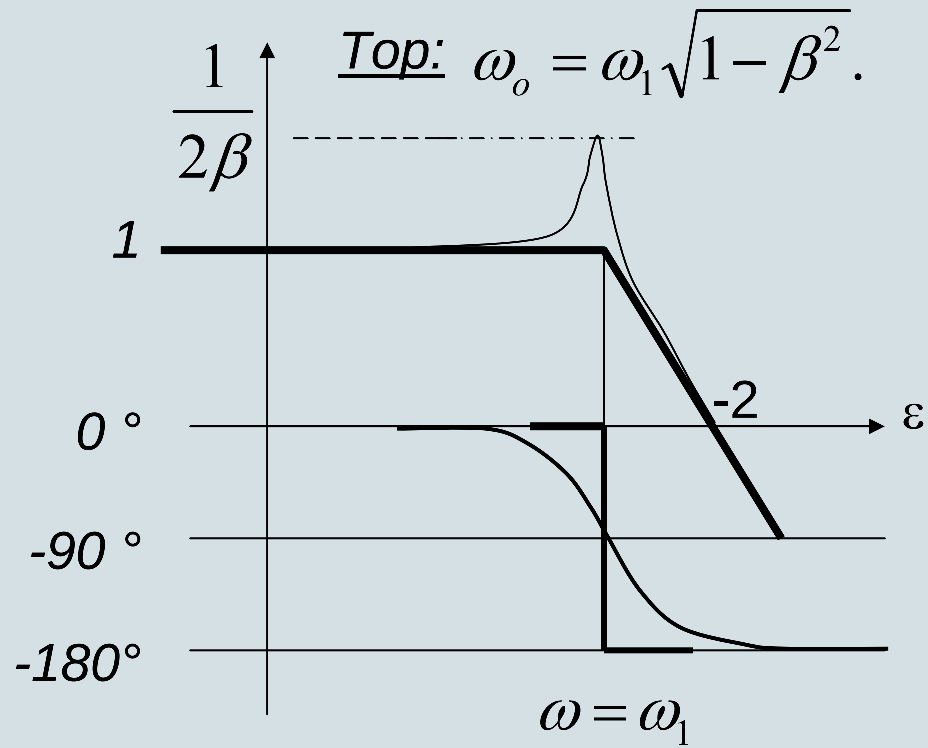
$$H = \frac{u}{\varepsilon} = k\left(1 + \frac{1}{\tau_i s}\right)\left(\frac{1+\tau_d s}{1+\frac{\tau_d s}{\gamma}}\right)$$



2nd order filter

$$H = \frac{u}{\varepsilon} = \frac{k}{\dfrac{s^2}{\omega_1^2} + 2\beta\dfrac{s}{\omega_1} + 1}$$

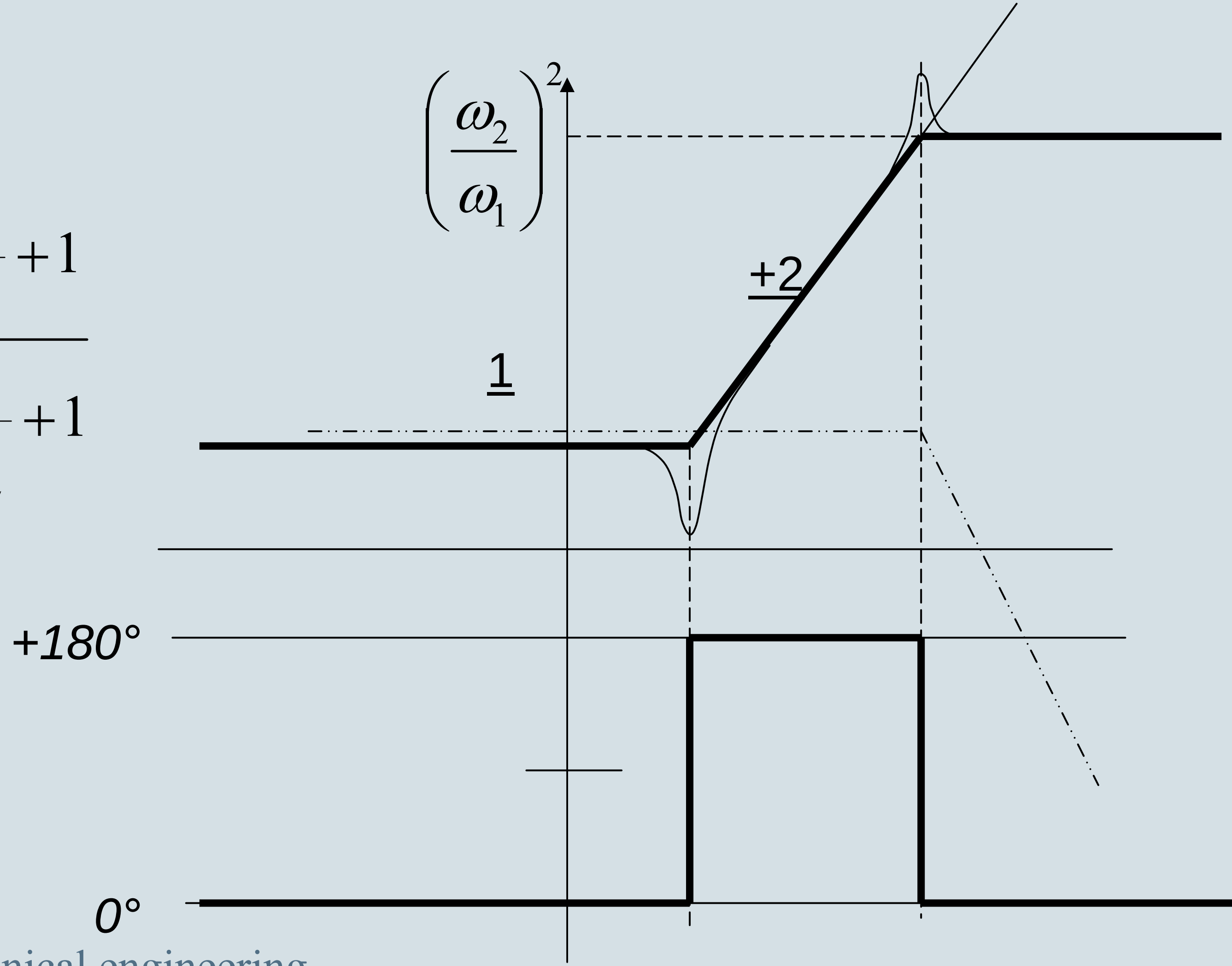


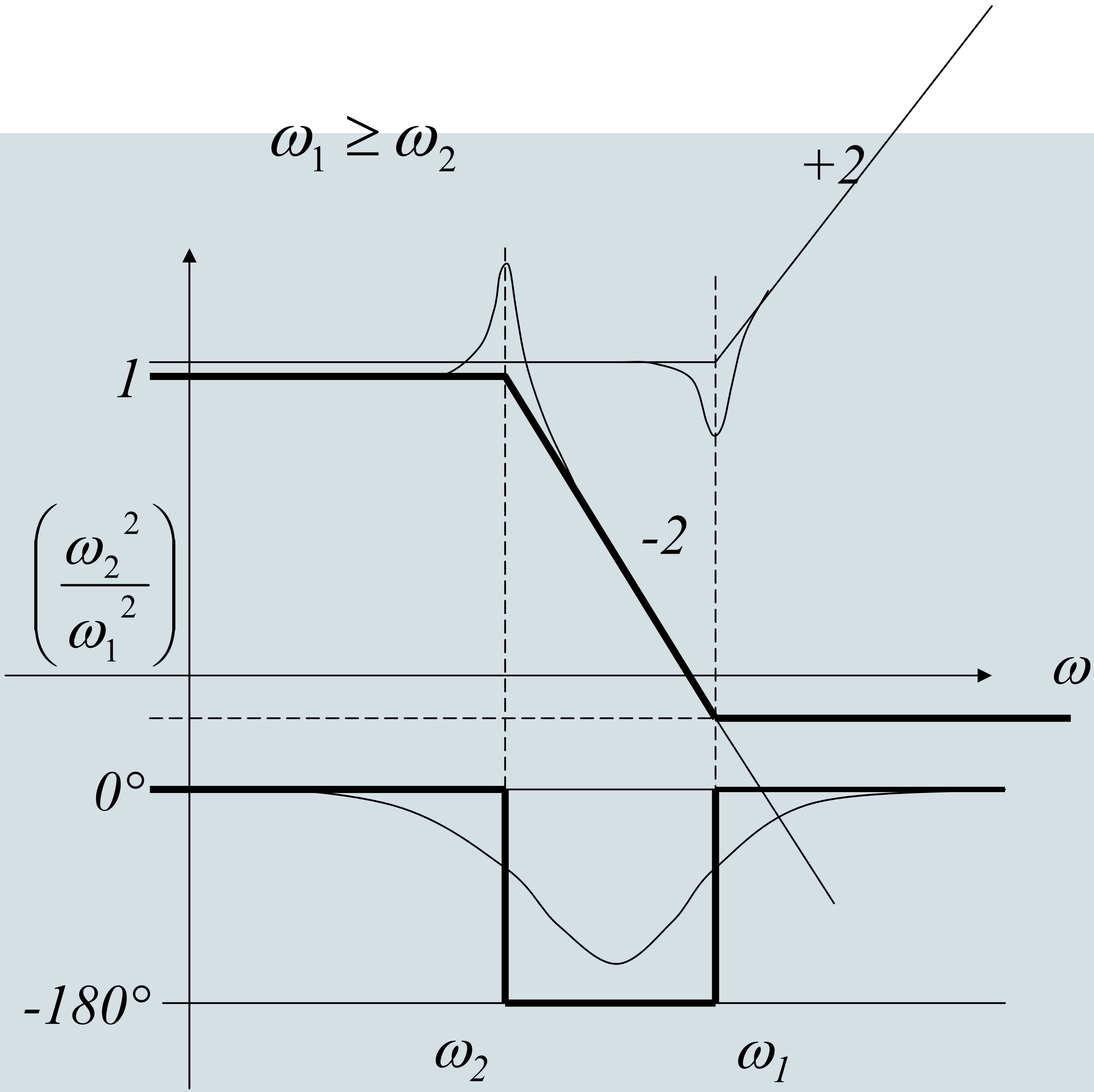


General 2nd order filters

General: $\omega_1 \neq \omega_2$

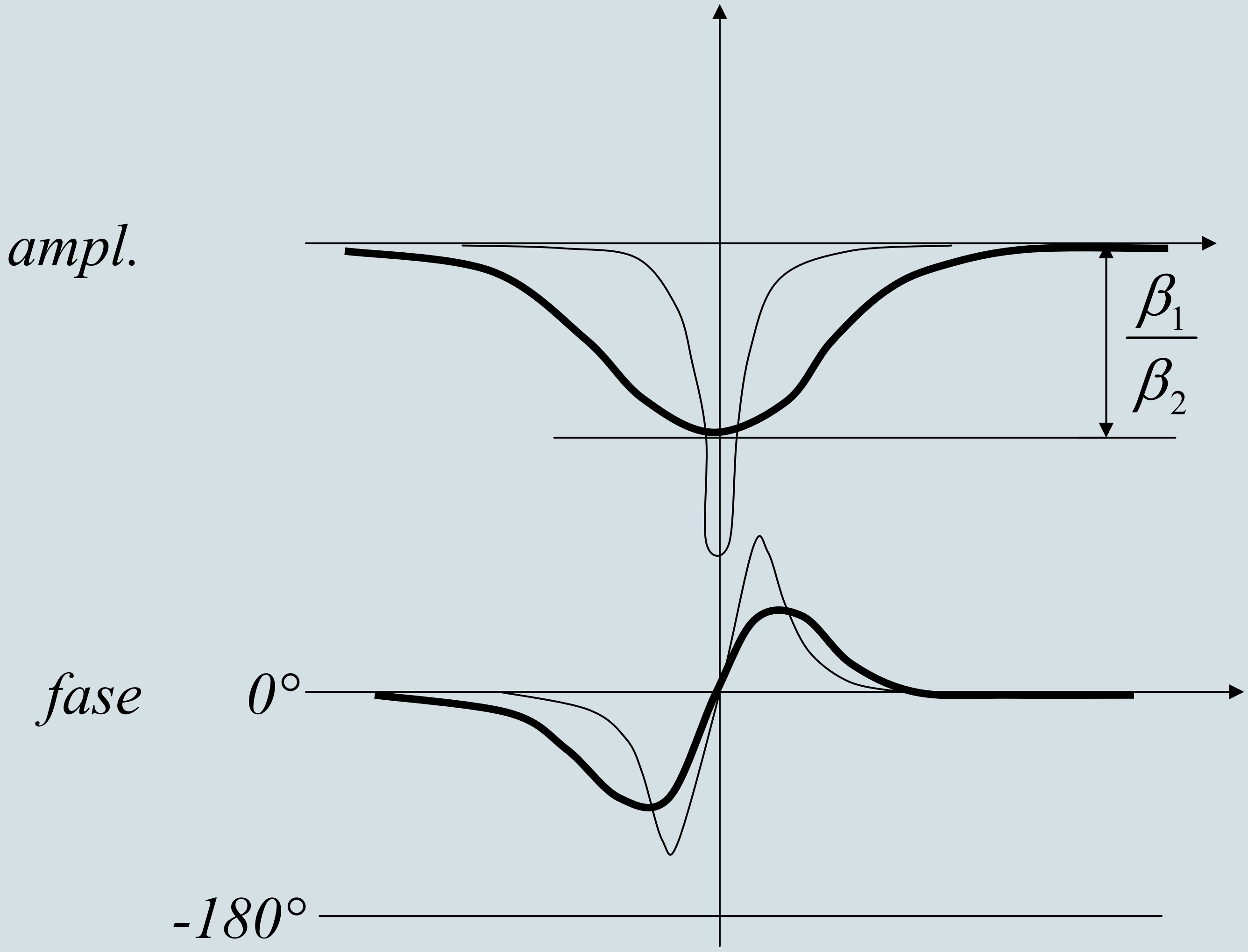
$$H = \frac{u}{\varepsilon} = \frac{\dfrac{s^2}{\omega_1^2} + 2\beta_1 \dfrac{s}{\omega_1} + 1}{\dfrac{s^2}{\omega_2^2} + 2\beta_2 \dfrac{s}{\omega_2} + 1}$$





$\omega_1 \geq \omega_2$
+2
1
-2
$\left(\frac{\omega_2^{\,2}}{\omega_1^{\,2}}\right)$
ω
0°
-180°
ω_2
ω_1

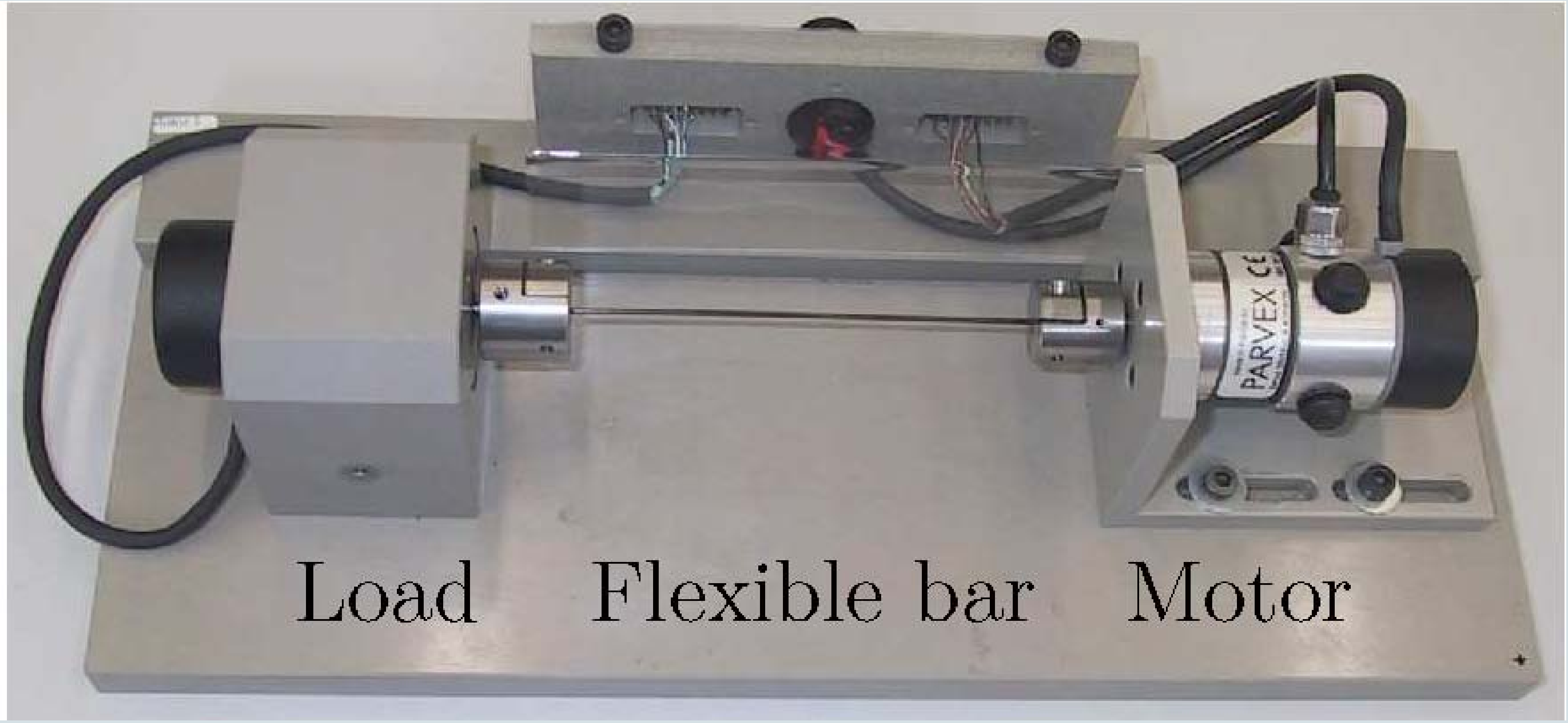
"Notch"-filter : $\omega_1 = \omega_2$

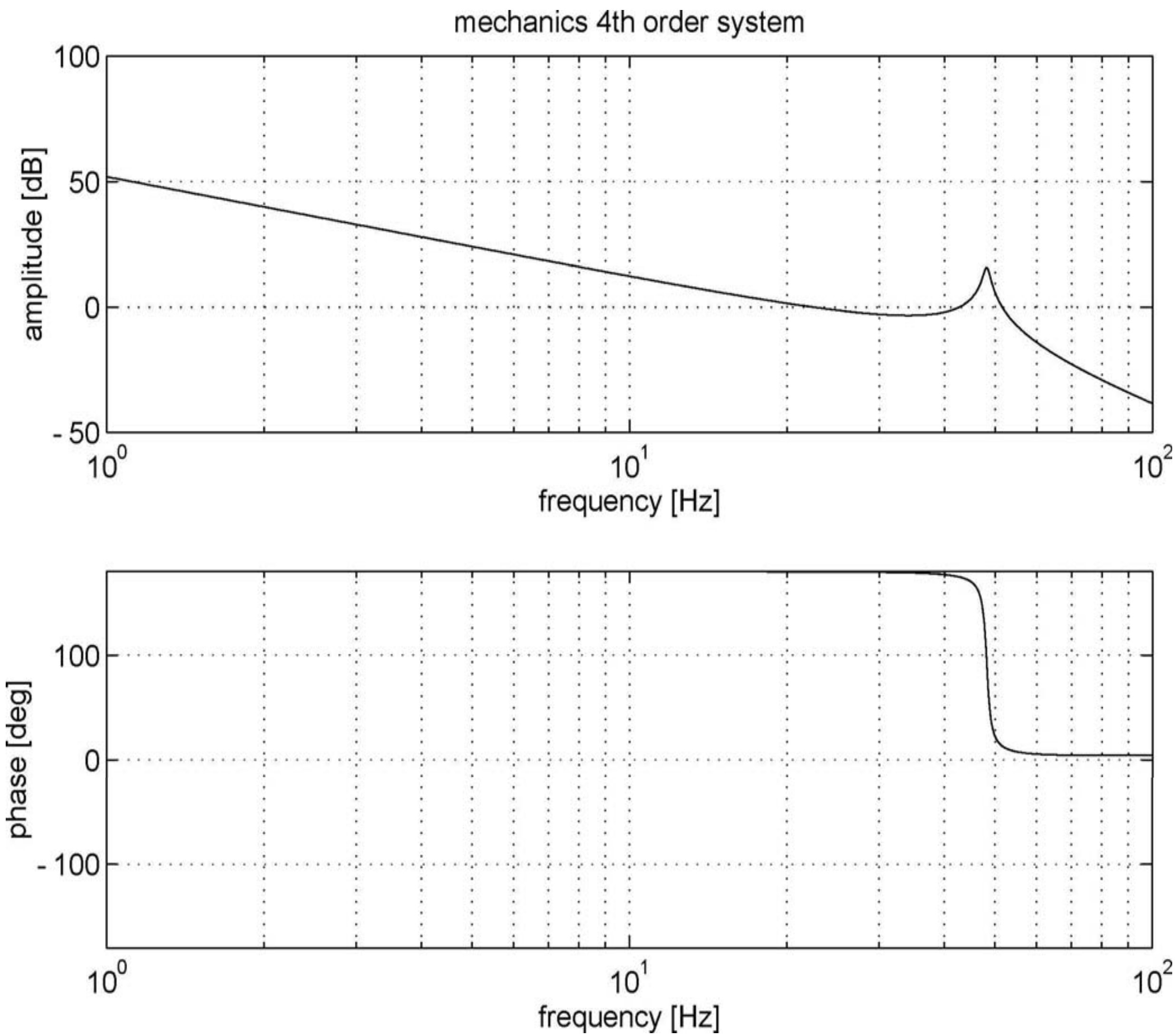


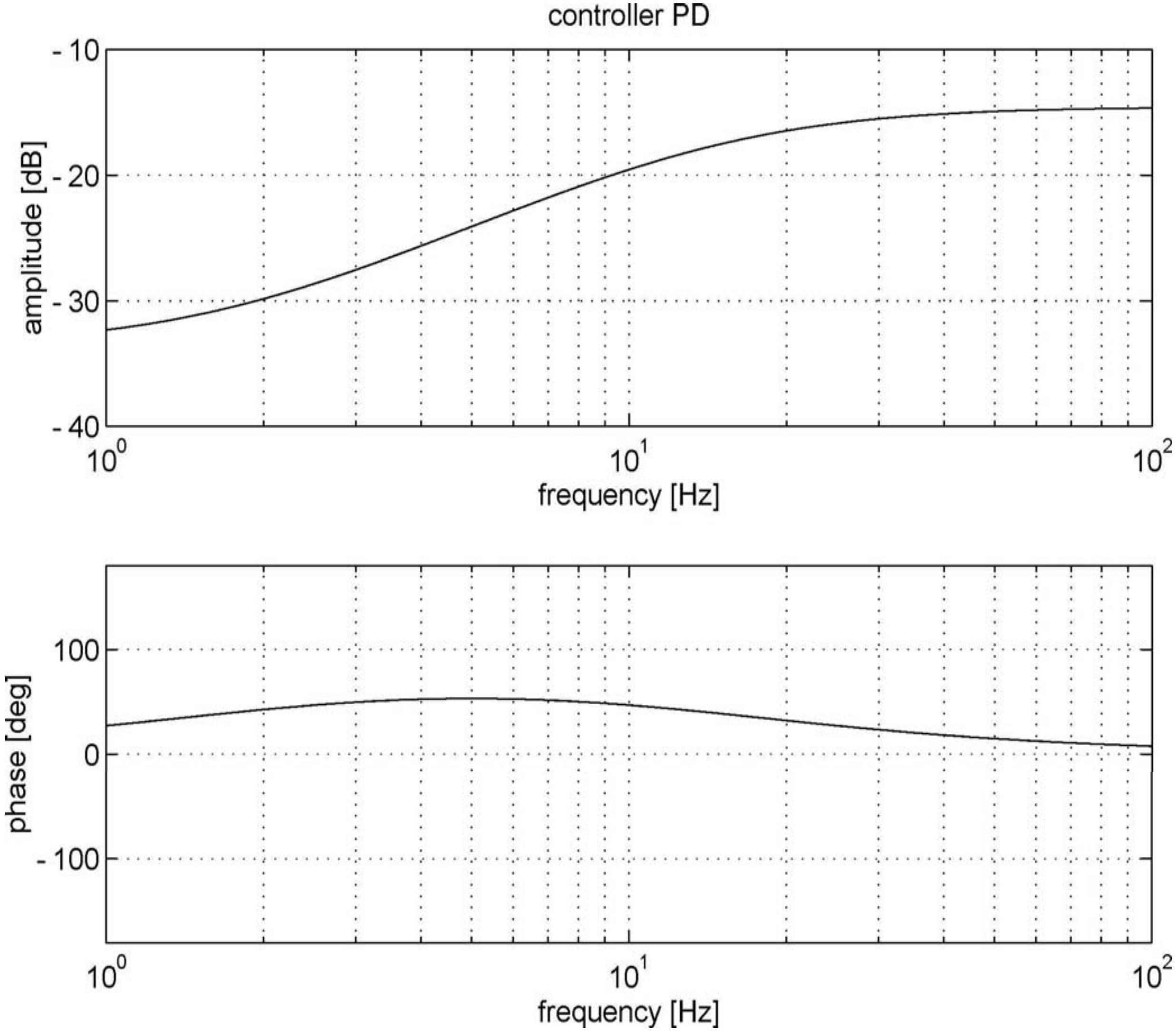
Loop shaping procedure for motion systems

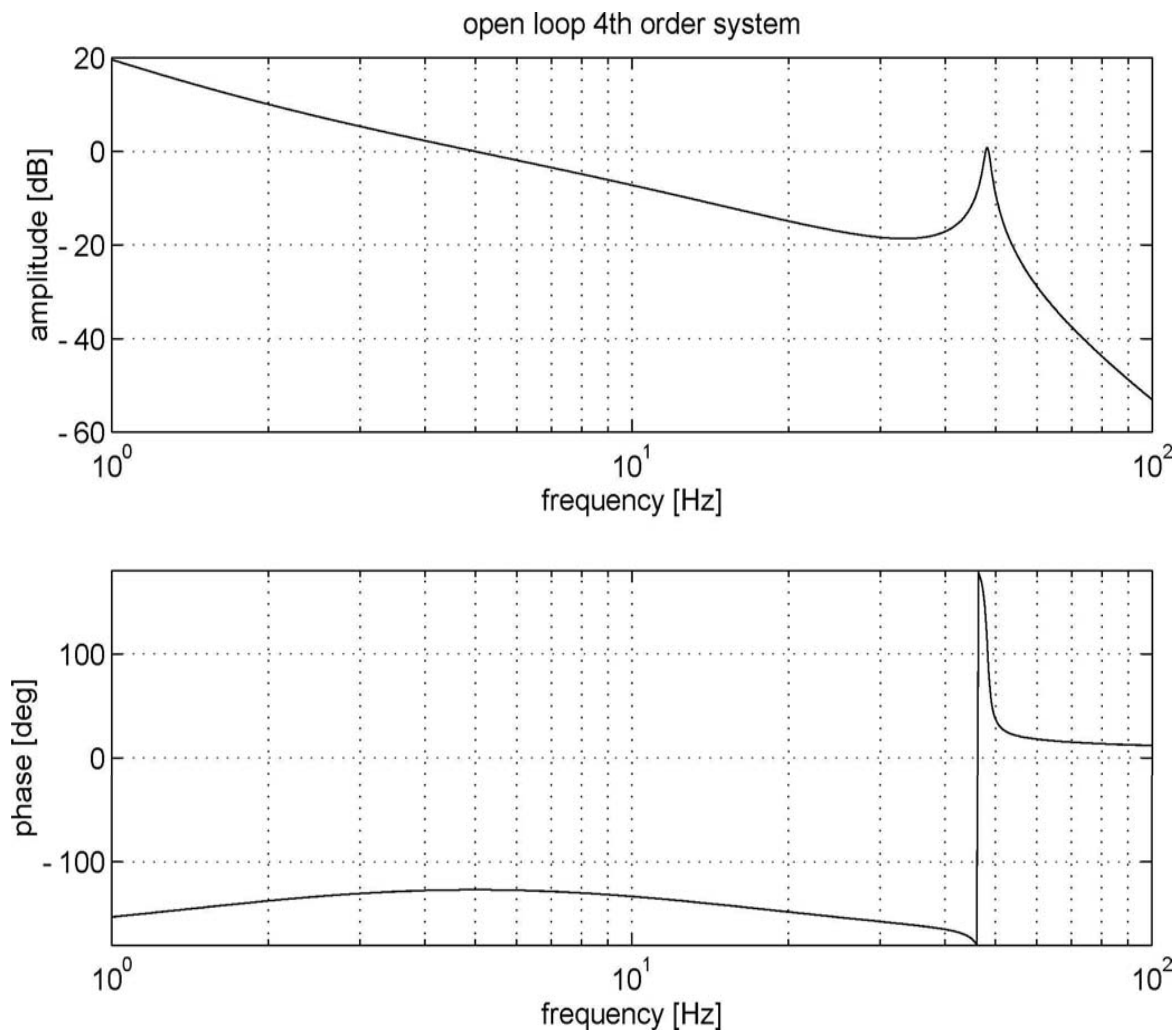
1. *stabilize the plant:*
   add lead/lag with zero = bandwidth/3 and pole = bandwidth*3,
   adjust gain to get stability;
   or add a pure PD with break point at the bandwidth
2. *add low-pass filter:*
   choose poles = bandwidth*6
3. *add notch if necessary,*
   or apply any other kind of first or second order filter and shape the loop
4. *add integral action:*
   choose zero = bandwidth/5
5. *increase bandwidth:*
   increase gain and zero/poles of integral action, lead/lag and
   other filters

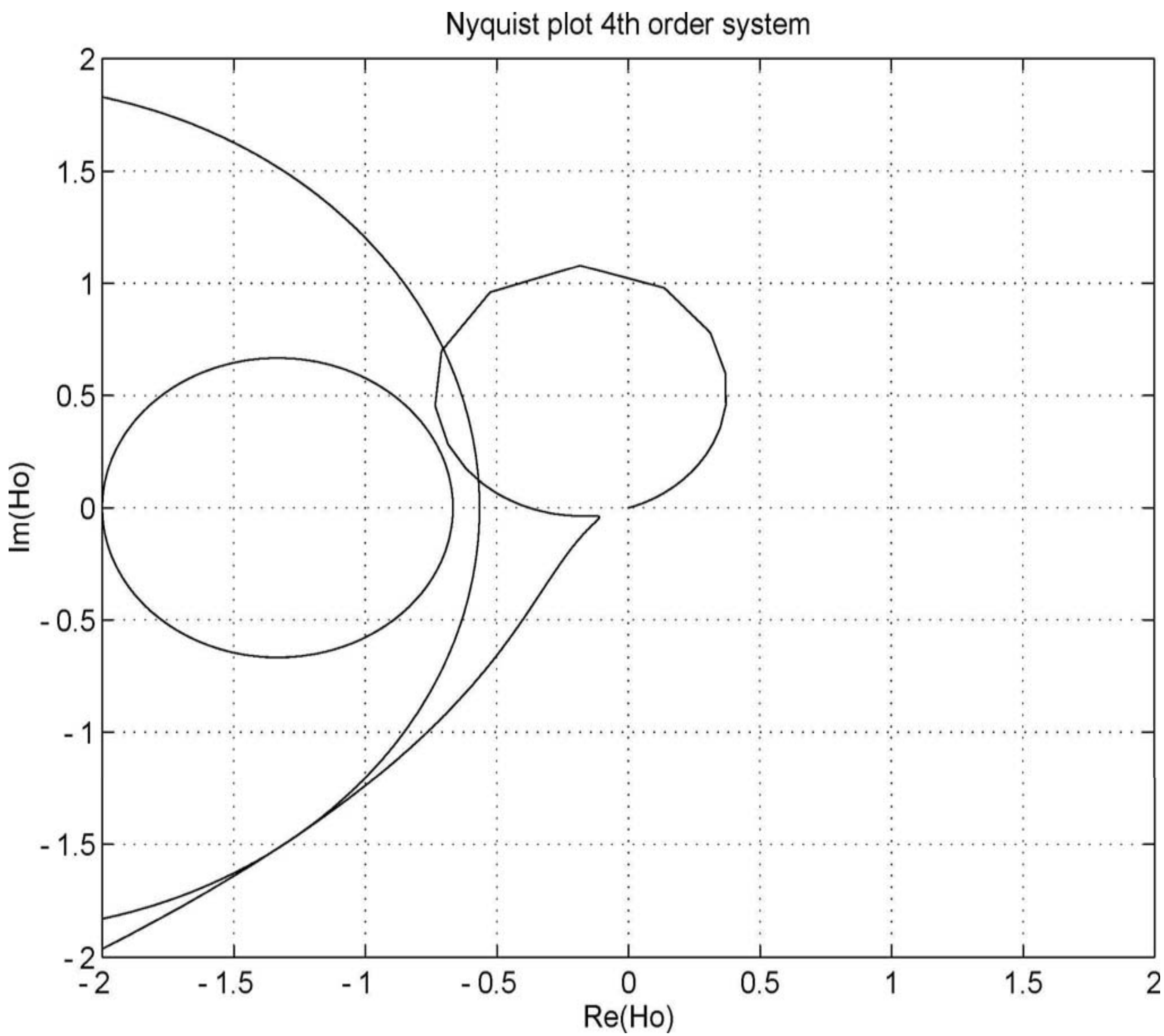
during steps 2-5: check all relevant transfer functions,
and relate to disturbance spectrum

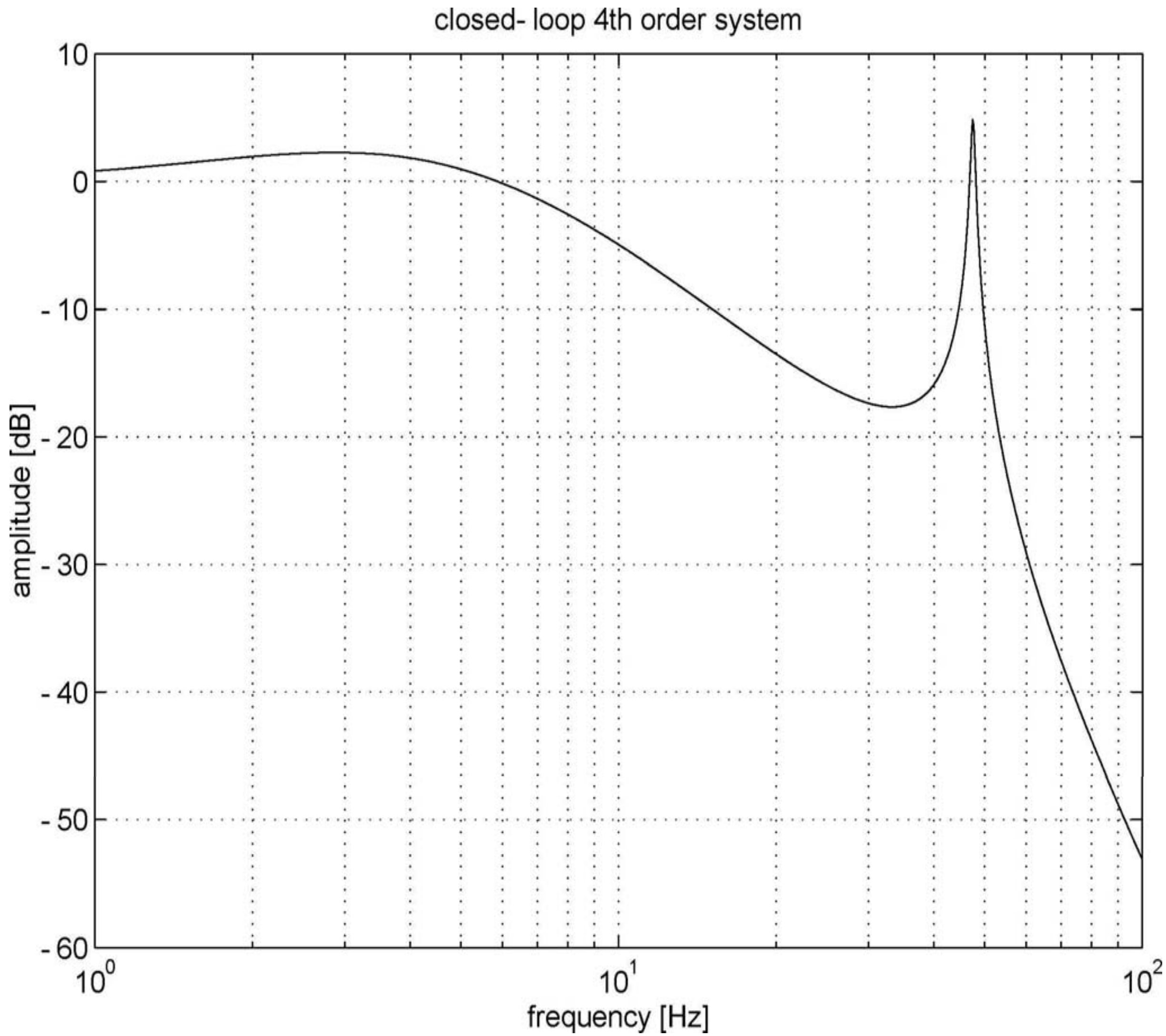

PARVEX
Load
Flexible bar
Motor


mechanics 4th order system
100
50
0
- 50
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]
100
0
- 100
phase [deg]
10^0
10^1
10^2
frequency [Hz]

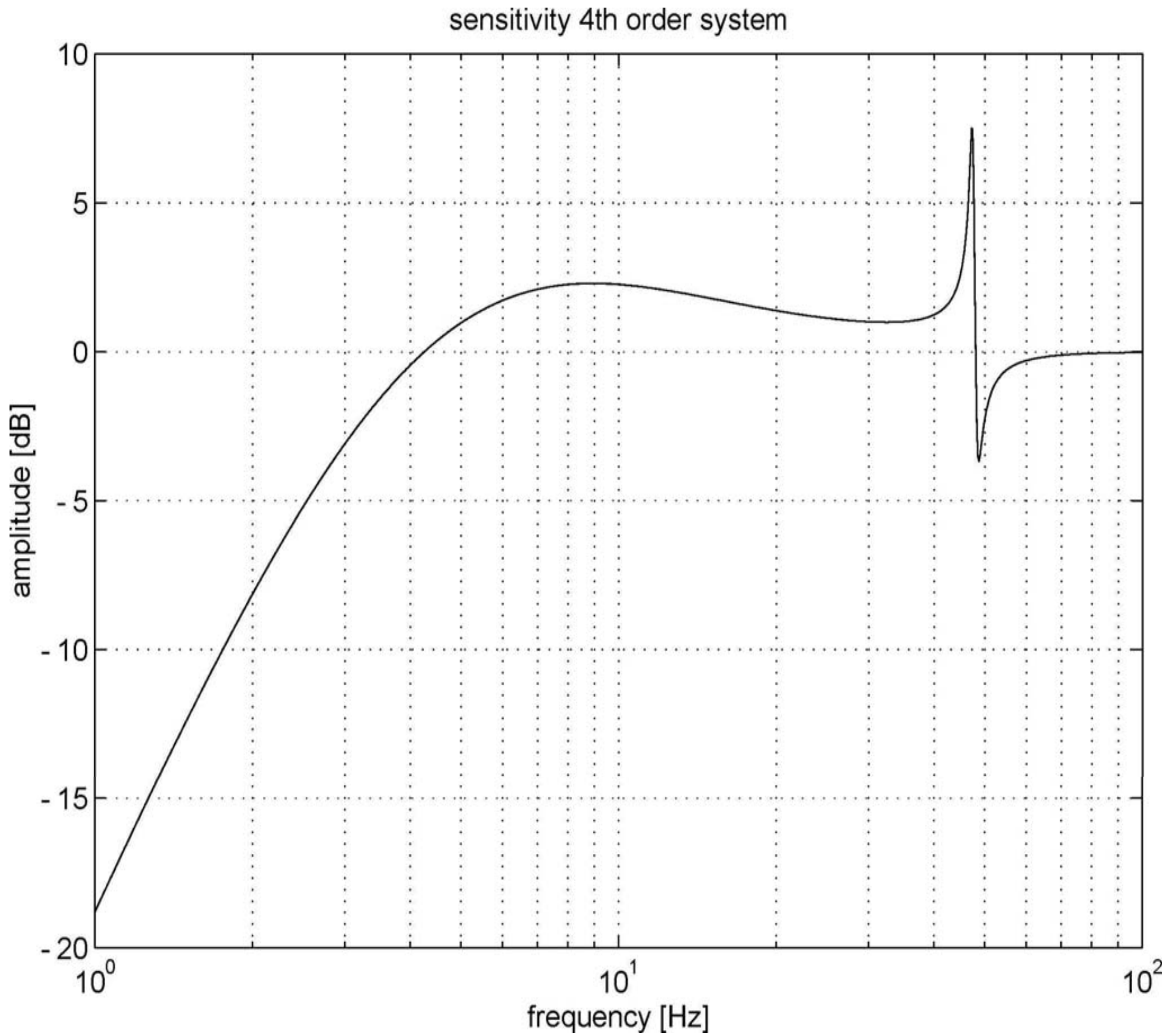

controller PD
amplitude [dB]
- 10
- 20
- 30
- 40
10^0
10^1
10^2
frequency [Hz]
phase [deg]
100
0
- 100
10^0
10^1
10^2
frequency [Hz]


open loop 4th order system
20
0
- 20
- 40
- 60
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]
100
0
- 100
phase [deg]
10^0
10^1
10^2
frequency [Hz]

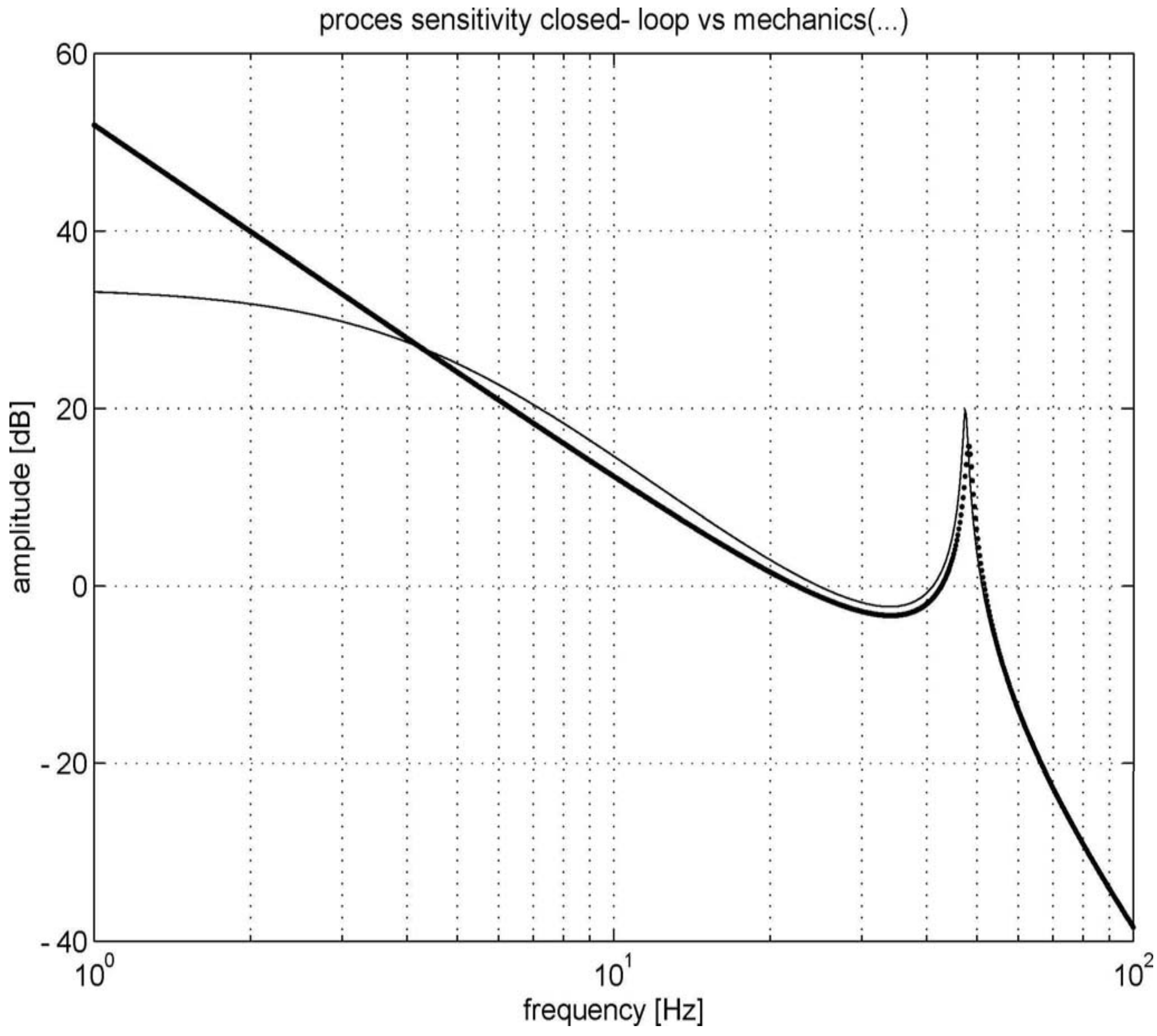

Nyquist plot 4th order system
Im(Ho)
Re(Ho)
2
1.5
1
0.5
0
- 0.5
- 1
- 1.5
- 2
- 2
- 1.5
- 1
- 0.5
0
0.5
1
1.5
2

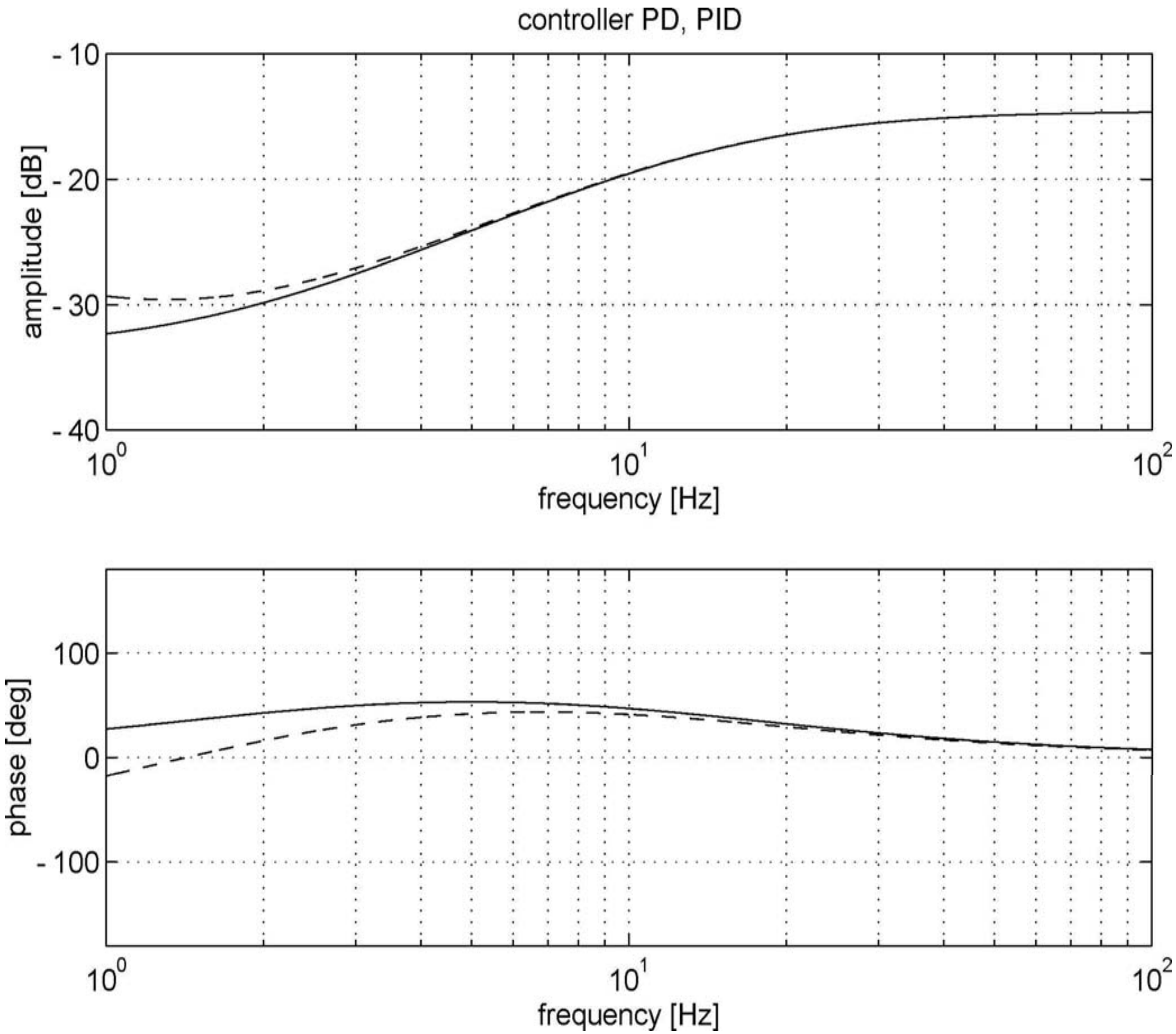


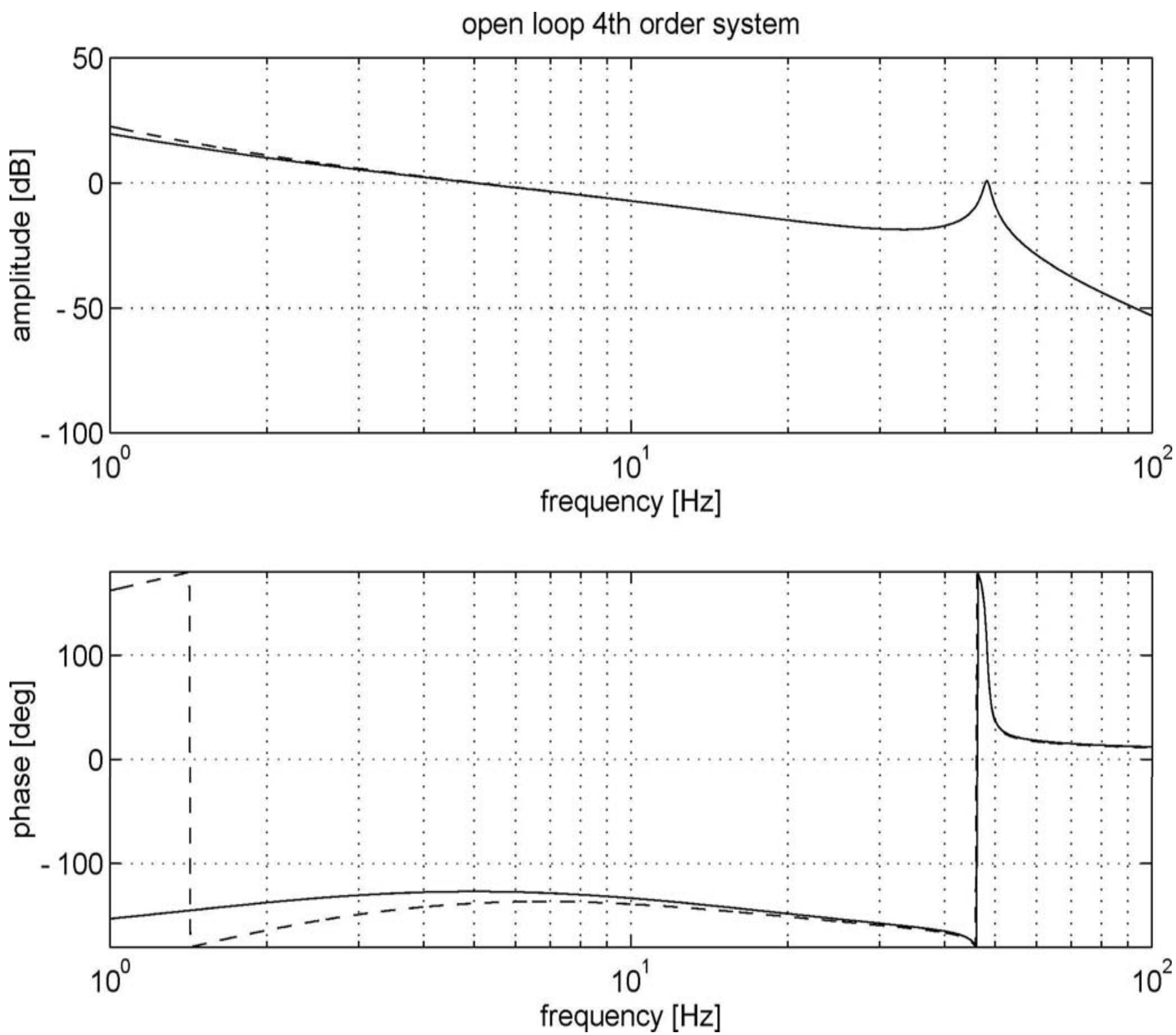
closed- loop 4th order system
10
0
- 10
- 20
- 30
- 40
- 50
- 60
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]



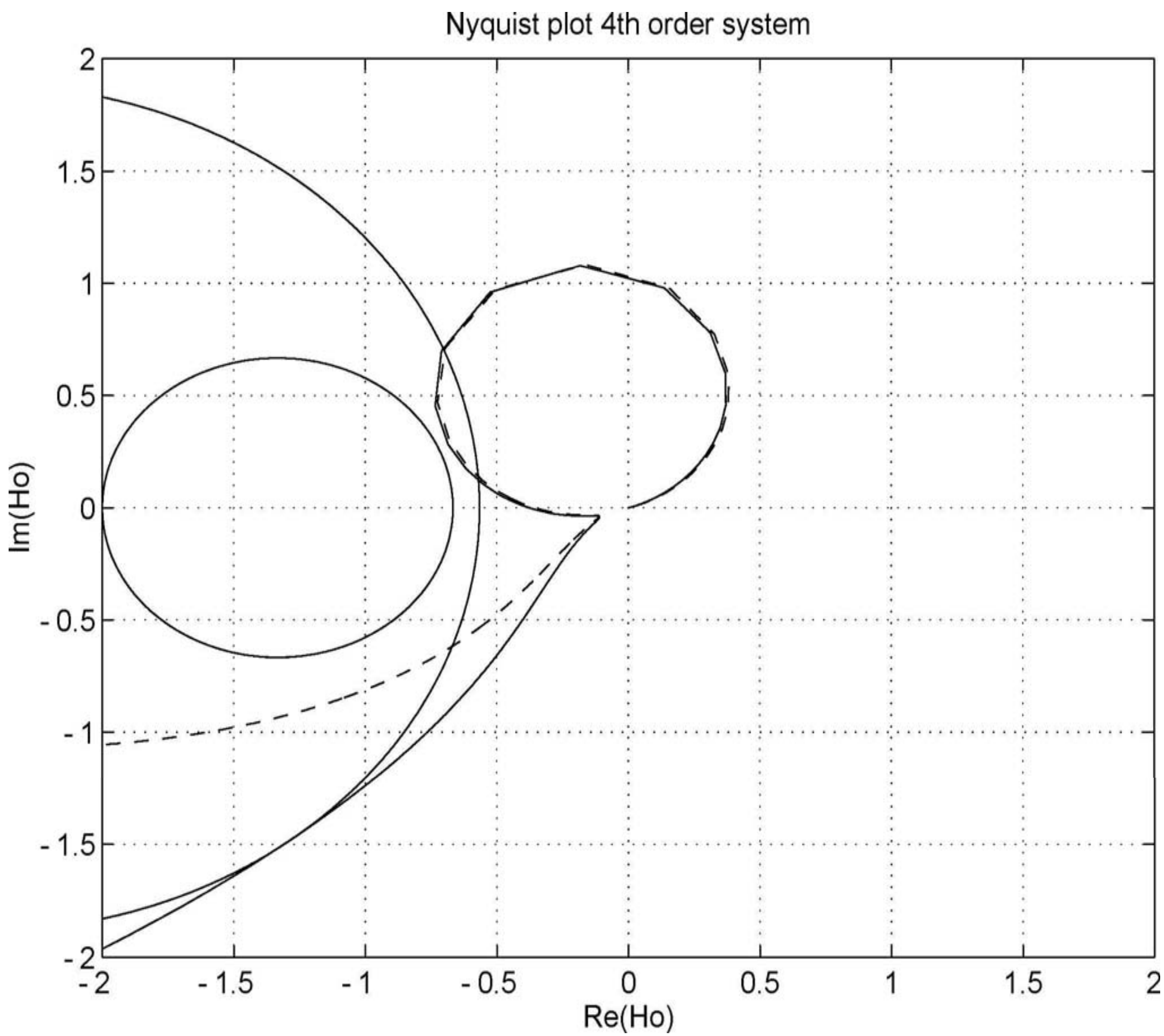
sensitivity 4th order system
amplitude [dB]
frequency [Hz]
10
5
0
- 5
- 10
- 15
- 20
10^0
10^1
10^2


proces sensitivity closed- loop vs mechanics(...)
amplitude [dB]
60
40
20
0
- 20
- 40
10^0
10^1
10^2
frequency [Hz]

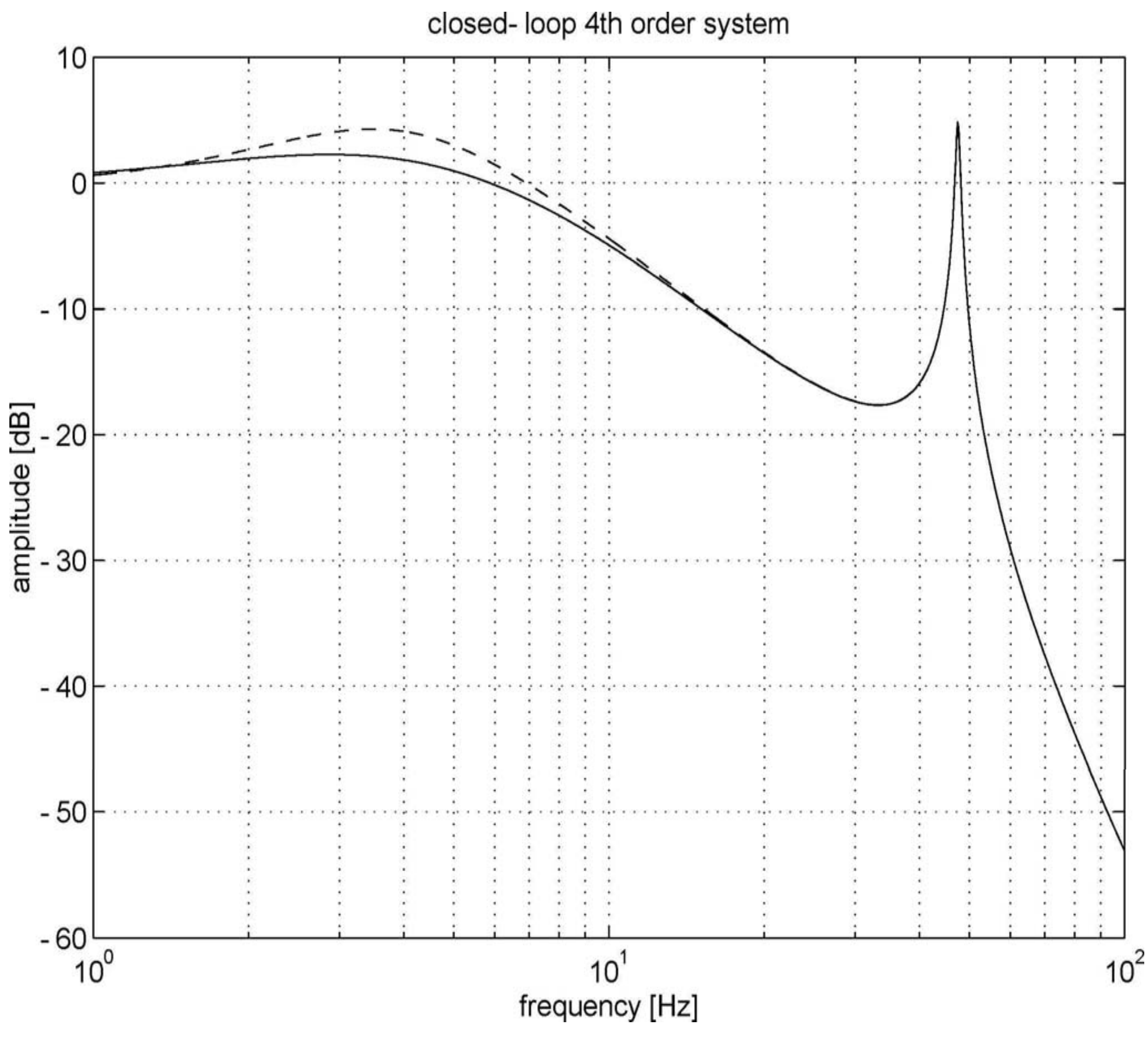

controller PD, PID
amplitude [dB]
- 10
- 20
- 30
- 40
10^0
10^1
10^2
frequency [Hz]
phase [deg]
100
0
- 100
10^0
10^1
10^2
frequency [Hz]



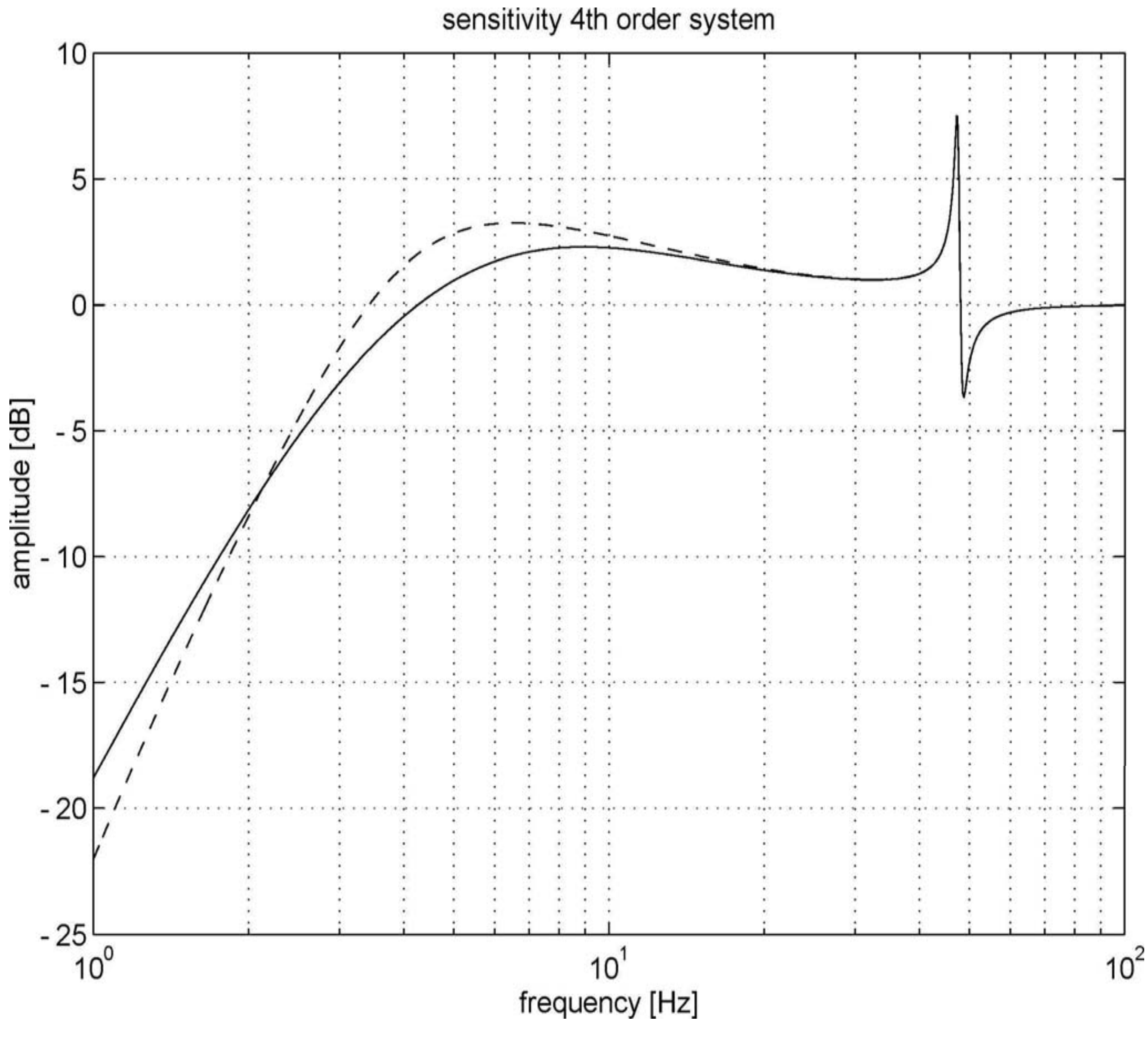
open loop 4th order system
50
0
- 50
- 100
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]
100
0
- 100
phase [deg]
10^0
10^1
10^2
frequency [Hz]

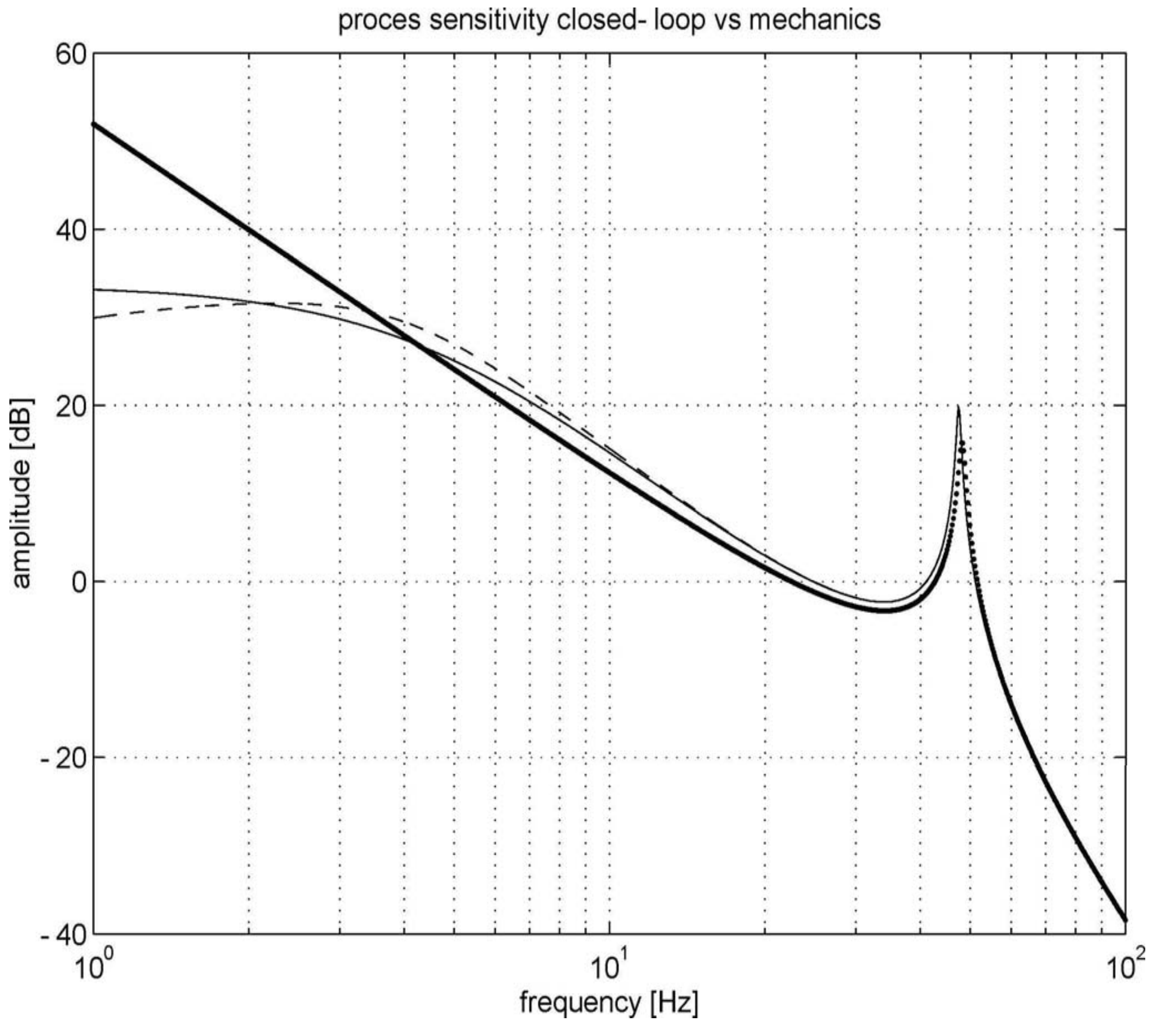


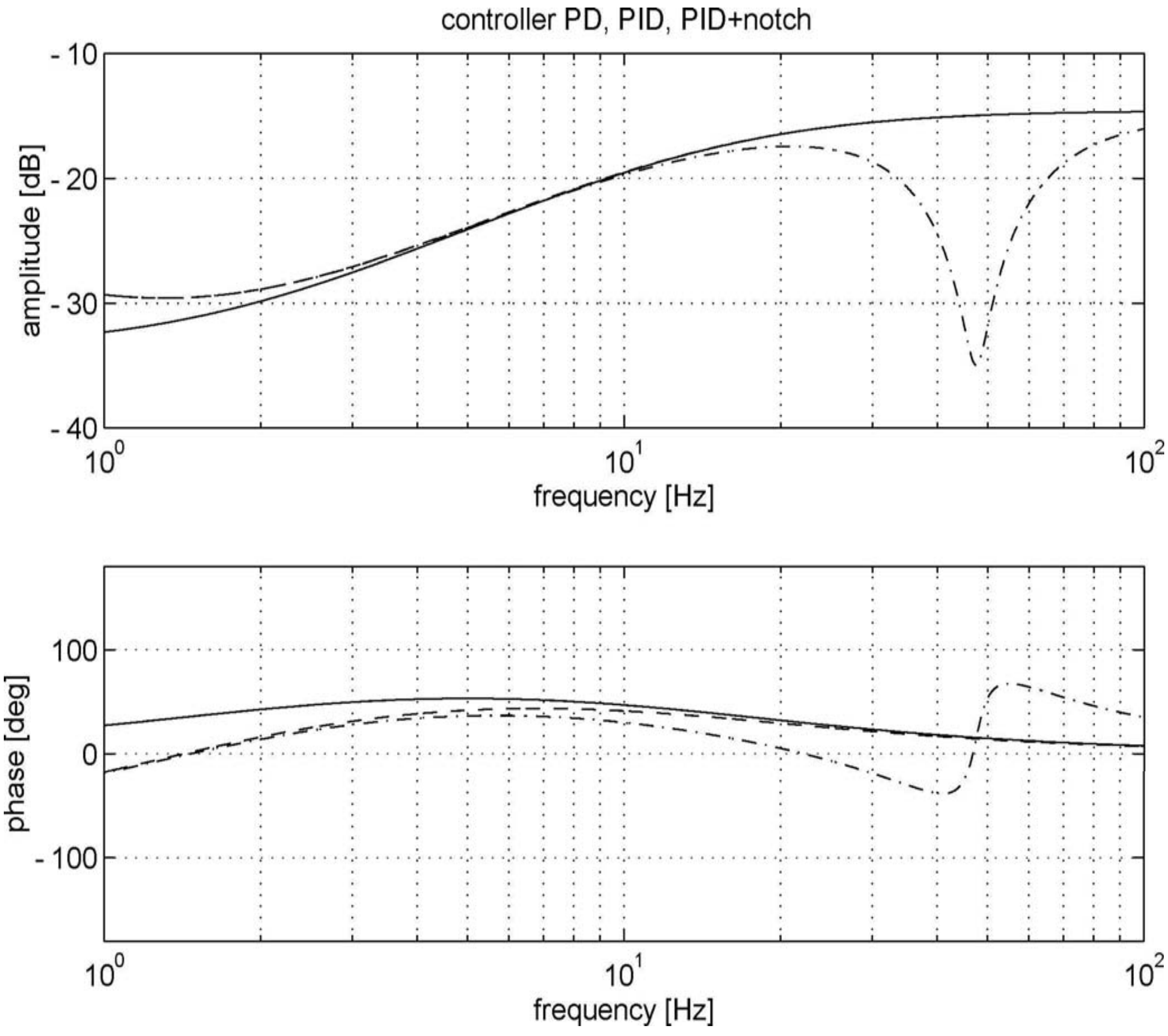
Nyquist plot 4th order system
2
1.5
1
0.5
0
- 0.5
- 1
- 1.5
- 2
- 2
- 1.5
- 1
- 0.5
0
0.5
1
1.5
2
Im(Ho)
Re(Ho)



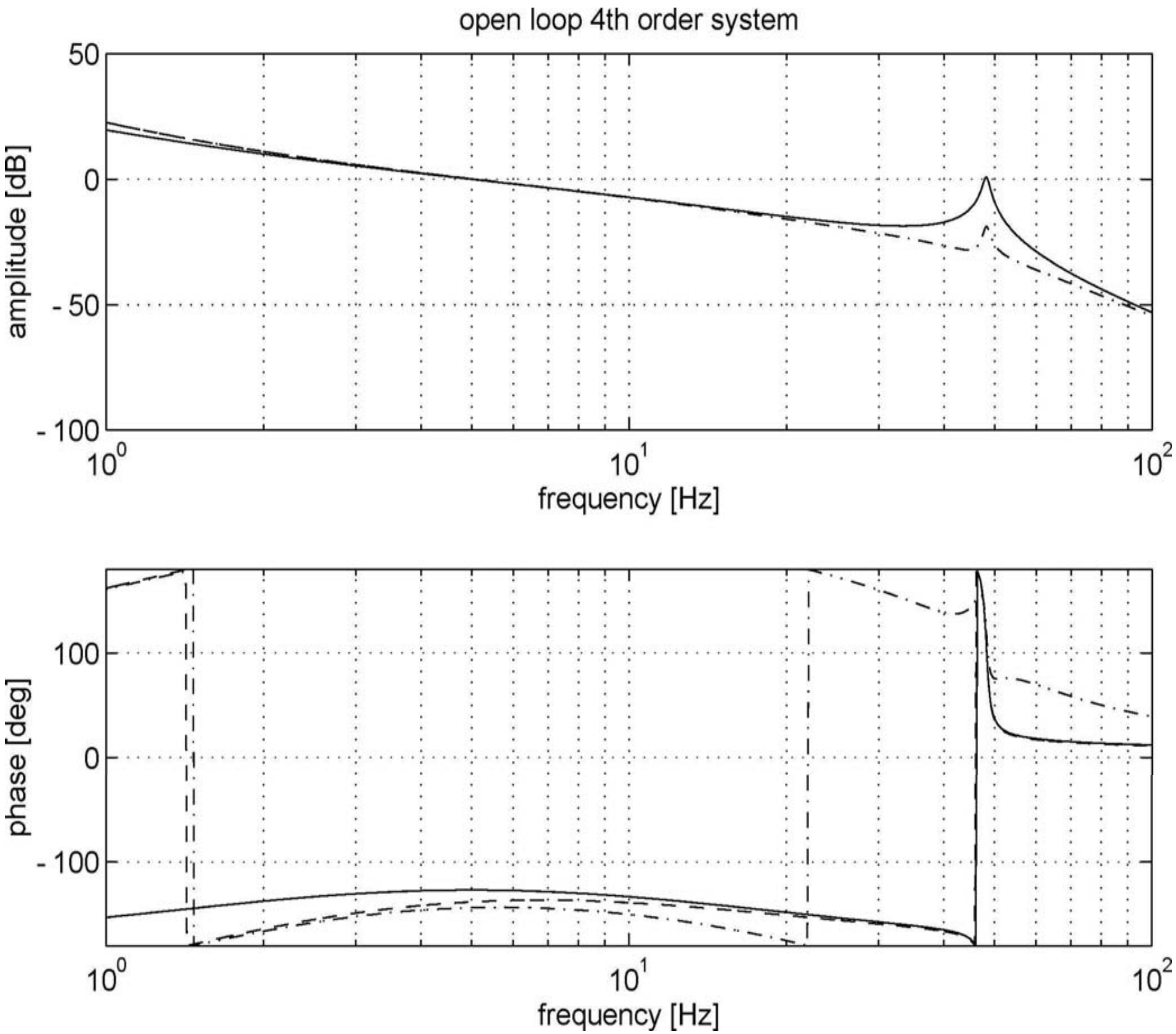
closed- loop 4th order system
10
0
- 10
- 20
- 30
- 40
- 50
- 60
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]


sensitivity 4th order system
10
5
0
- 5
- 10
- 15
- 20
- 25
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]

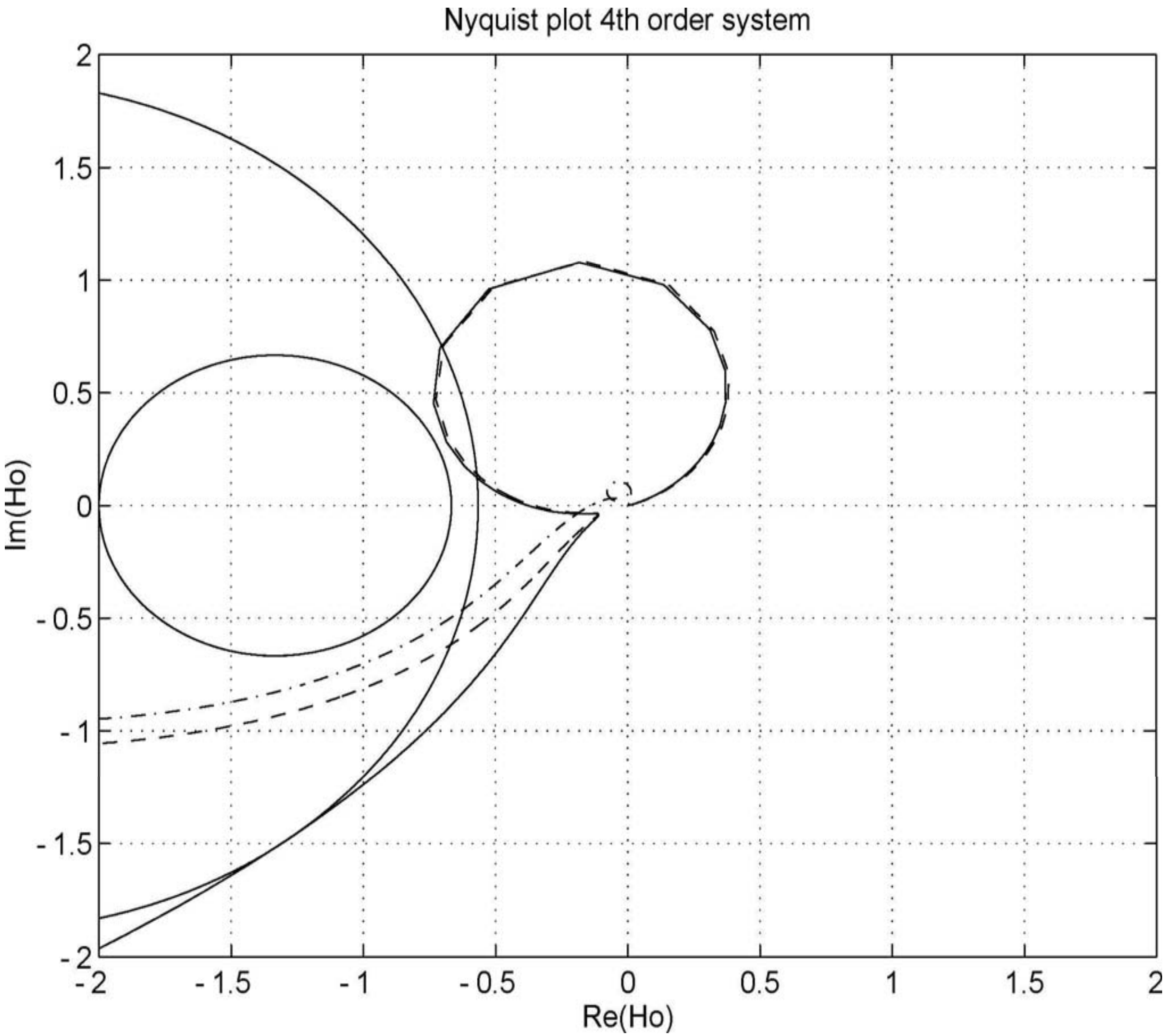

proces sensitivity closed- loop vs mechanics
60
40
20
0
- 20
- 40
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]

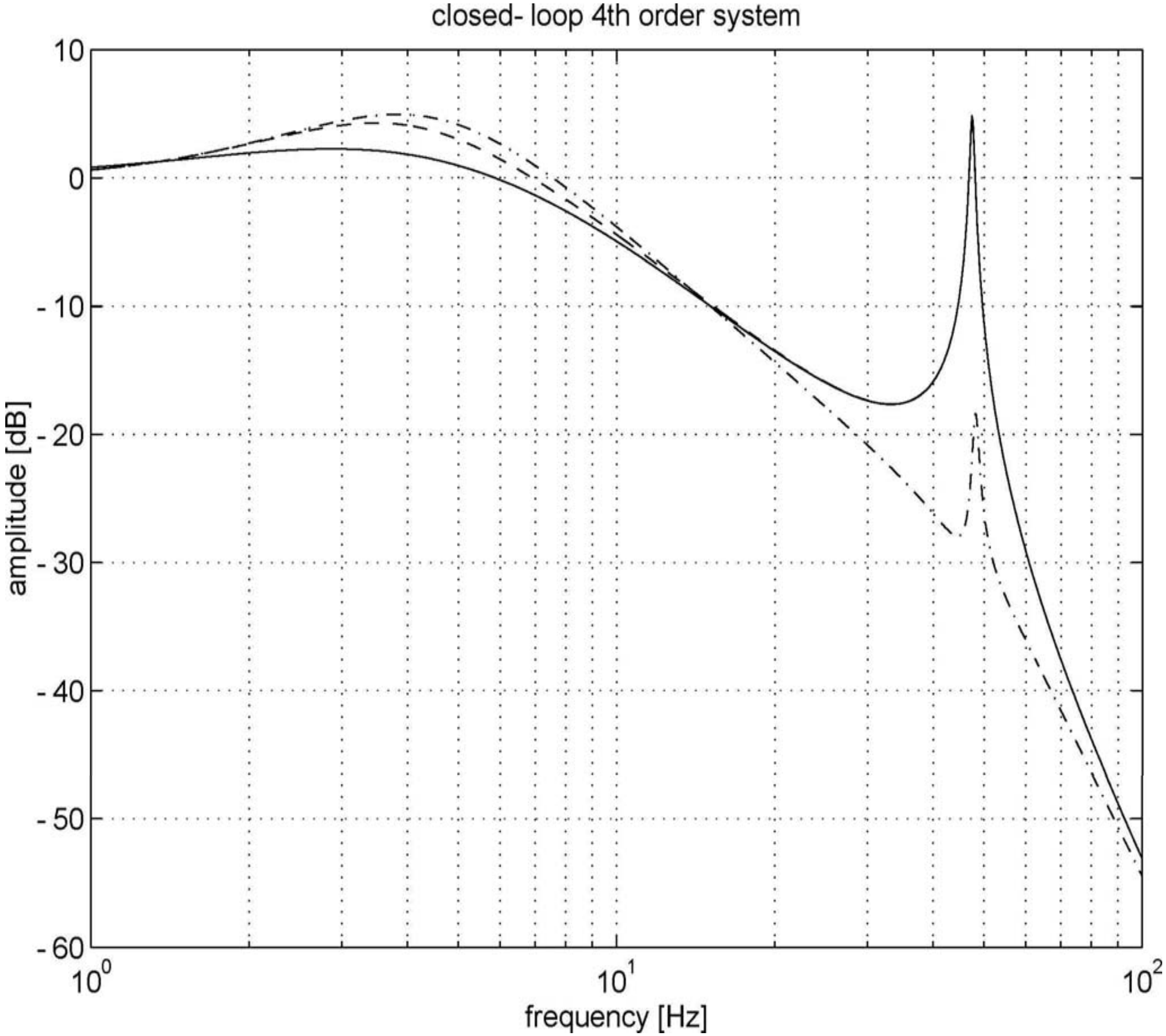


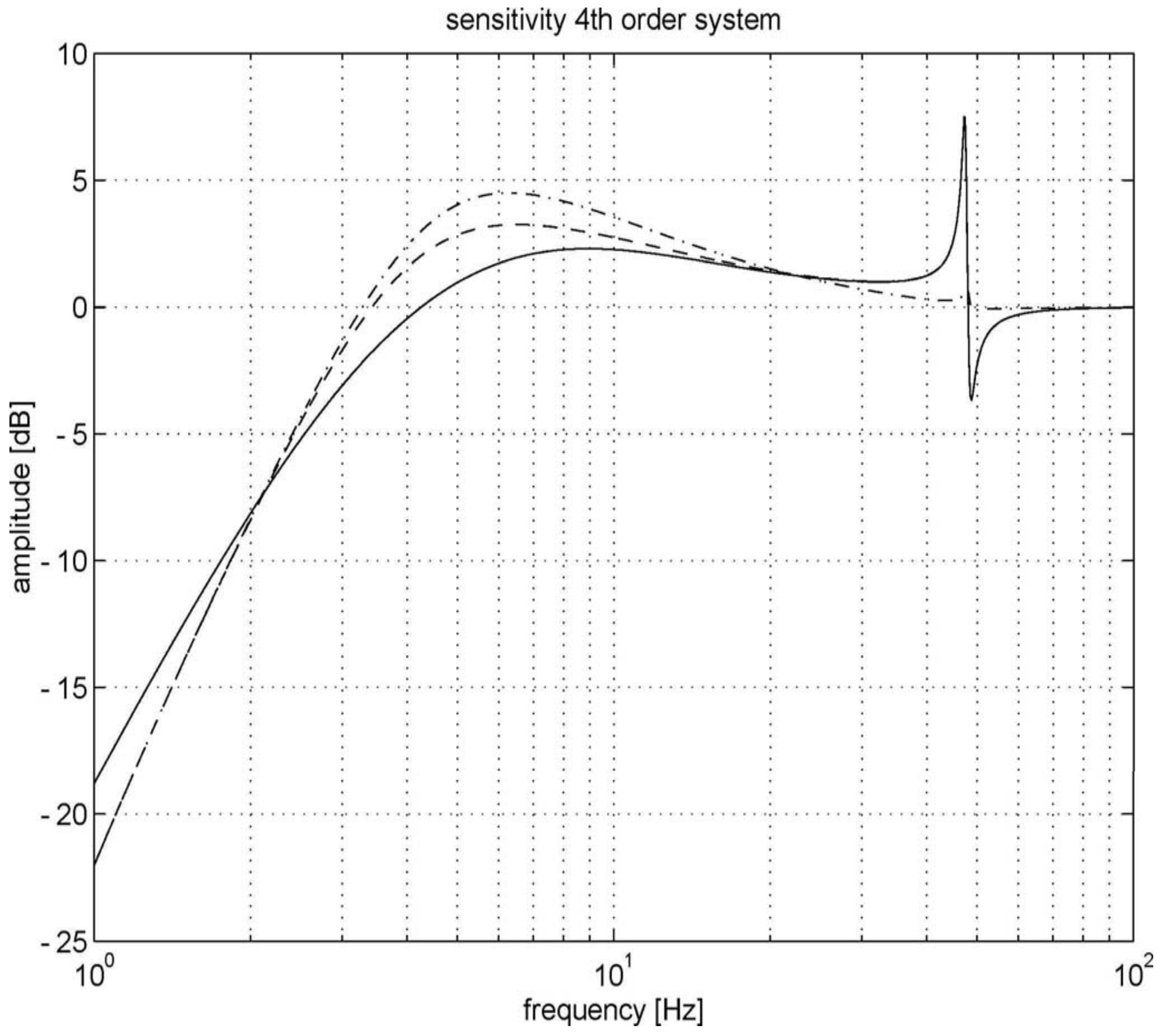
controller PD, PID, PID+notch
- 10
- 20
- 30
- 40
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]
100
0
- 100
phase [deg]
10^0
10^1
10^2
frequency [Hz]

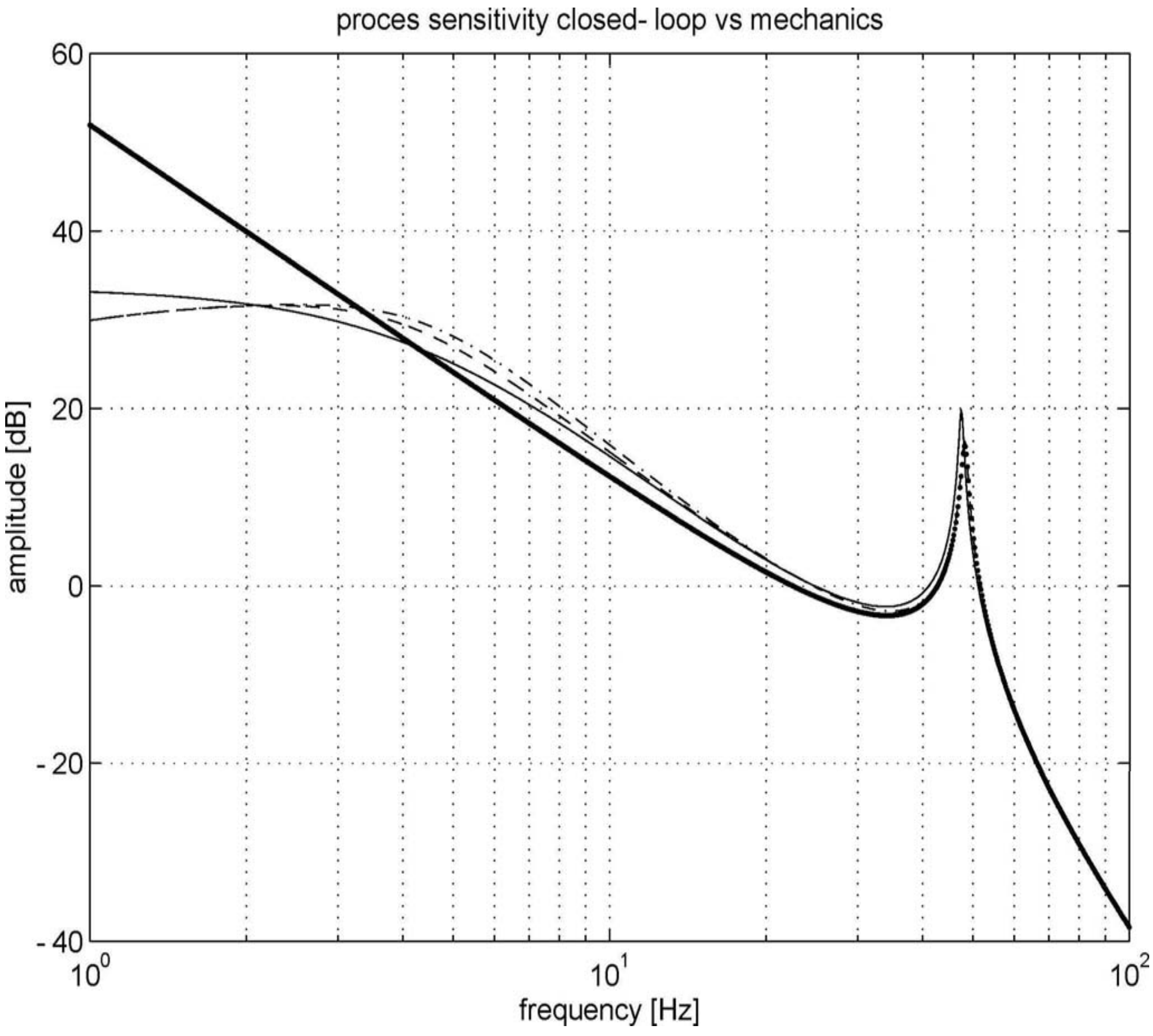


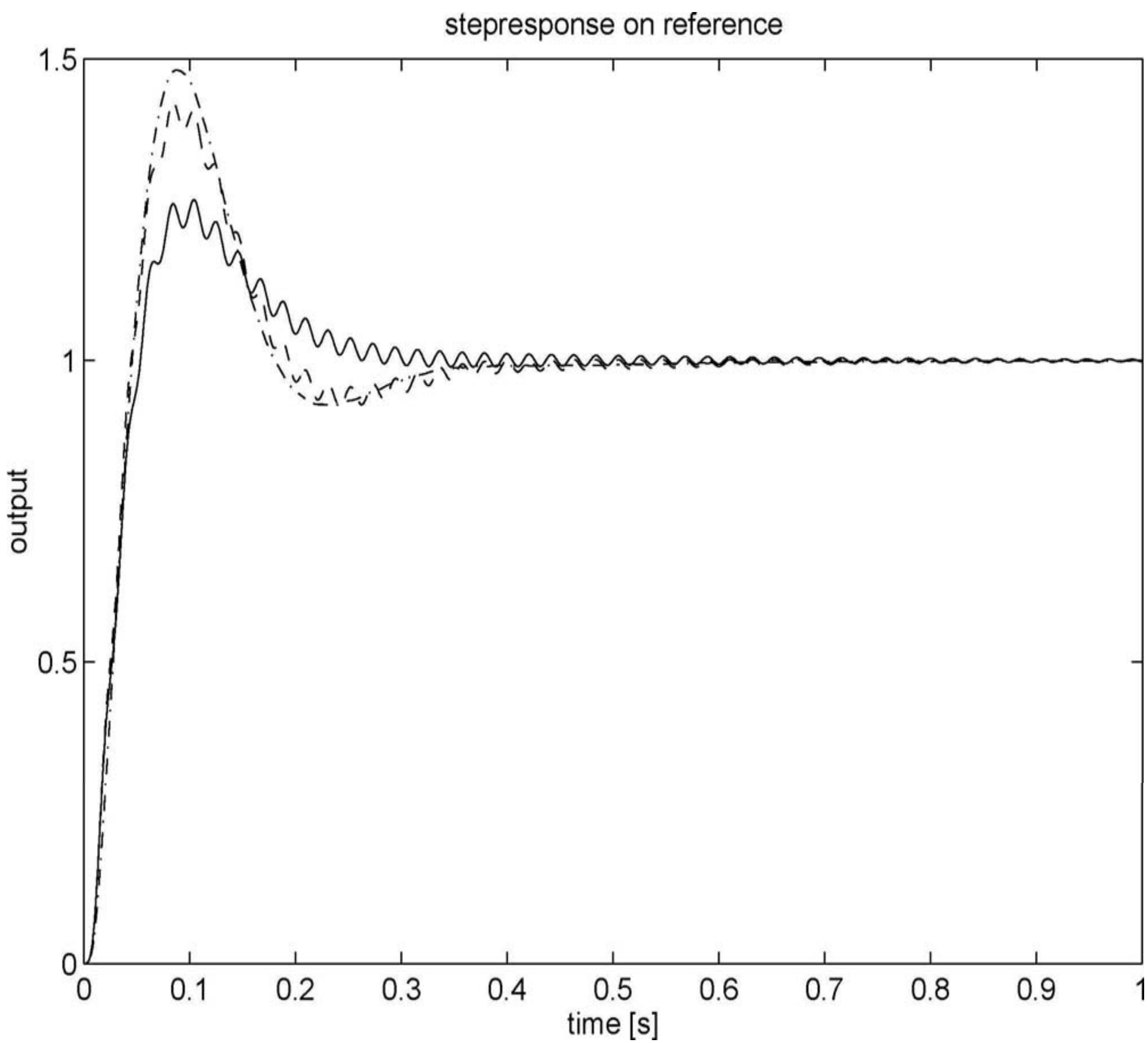
open loop 4th order system
50
0
- 50
- 100
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]
100
0
- 100
phase [deg]
10^0
10^1
10^2
frequency [Hz]


Nyquist plot 4th order system
Im(Ho)
Re(Ho)
2
1.5
1
0.5
0
- 0.5
- 1
- 1.5
- 2
- 2
- 1.5
- 1
- 0.5
0
0.5
1
1.5
2

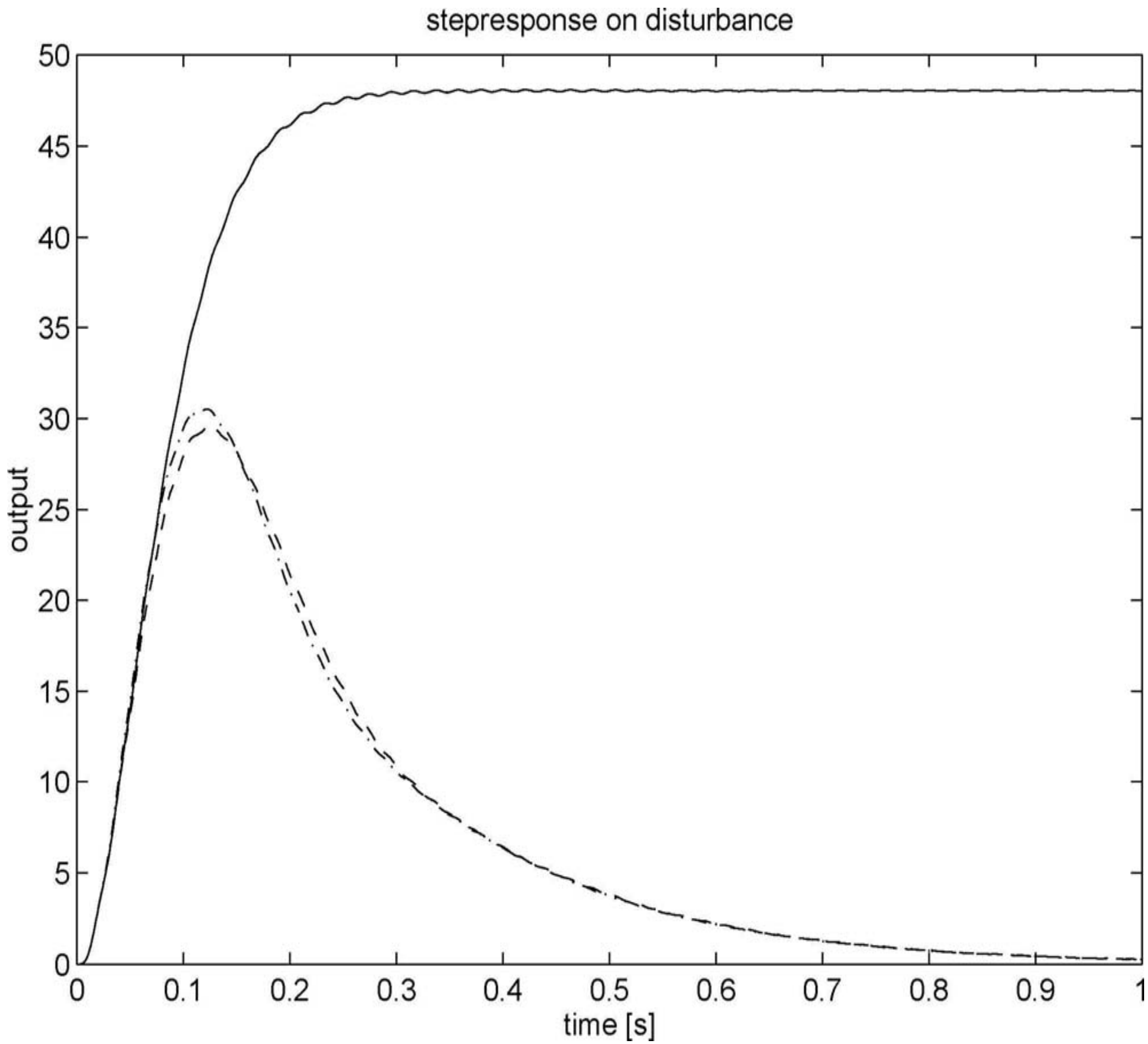

closed- loop 4th order system
10
0
- 10
- 20
- 30
- 40
- 50
- 60
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]


sensitivity 4th order system
10
5
0
- 5
- 10
- 15
- 20
- 25
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]


proces sensitivity closed- loop vs mechanics
60
40
20
0
- 20
- 40
amplitude [dB]
10^0
10^1
10^2
frequency [Hz]



stepresponse on reference
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
output
time [s]


stepresponse on disturbance
output
time [s]
0
5
10
15
20
25
30
35
40
45
50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Implementation issues

1. sampling = delay: linear phase lag

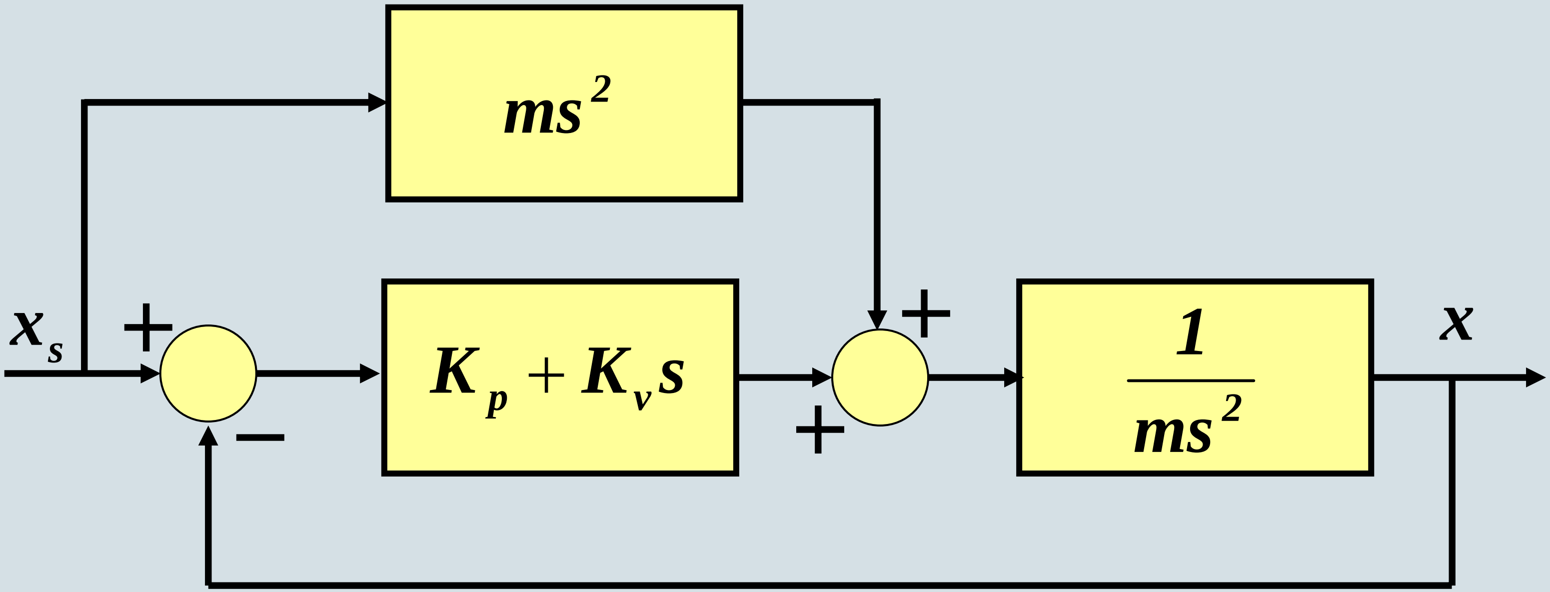
for example: sampling at 4 kHz gives phase lag due to Zero-Order-Hold of:

180º	@ 4 kHz
18º	@ 400 Hz
9º	@ 200 Hz

2. Delay due to calculations
3. Quantization (sensors, digital representation)

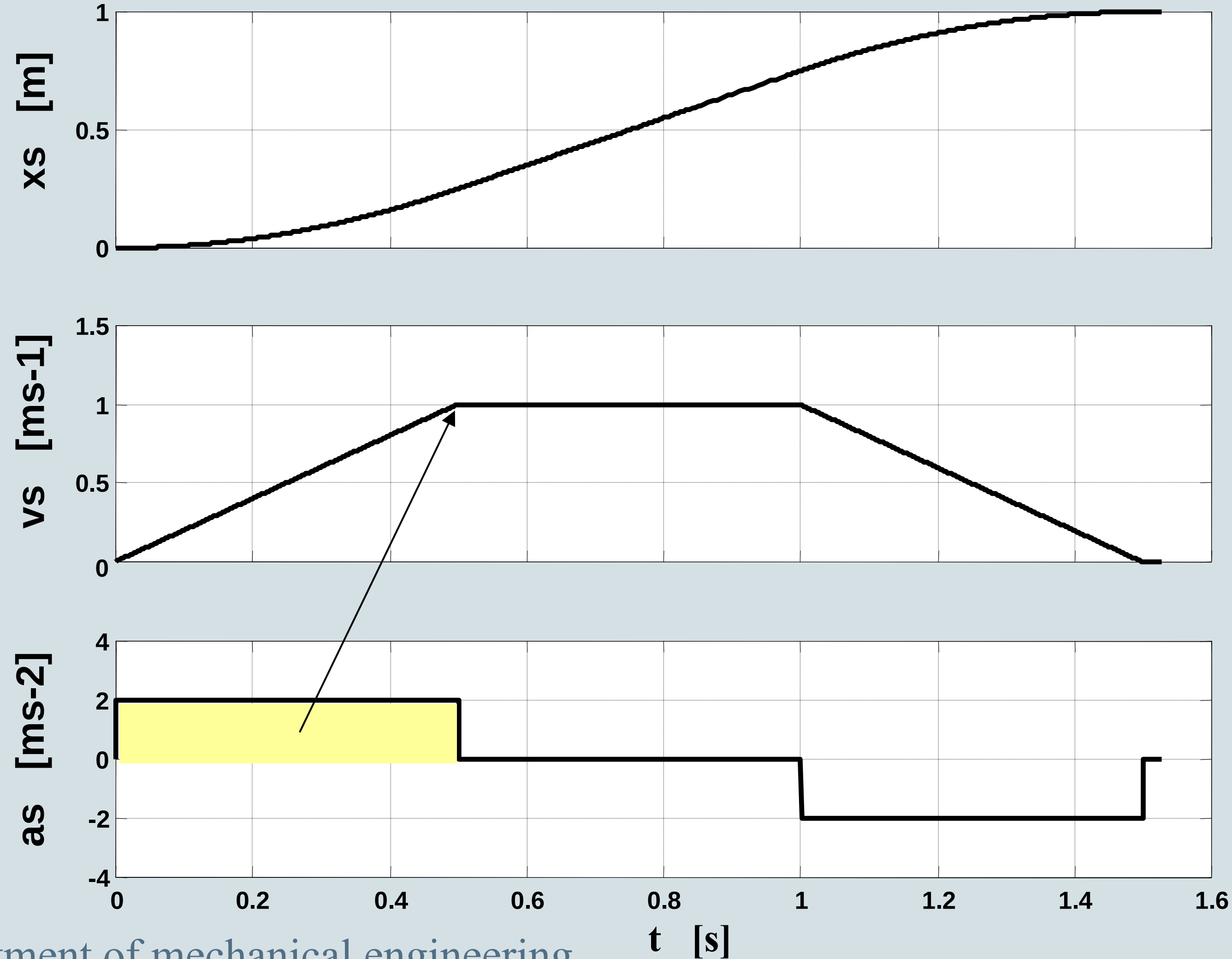
Feedforward design

Feedforward based on inverse model



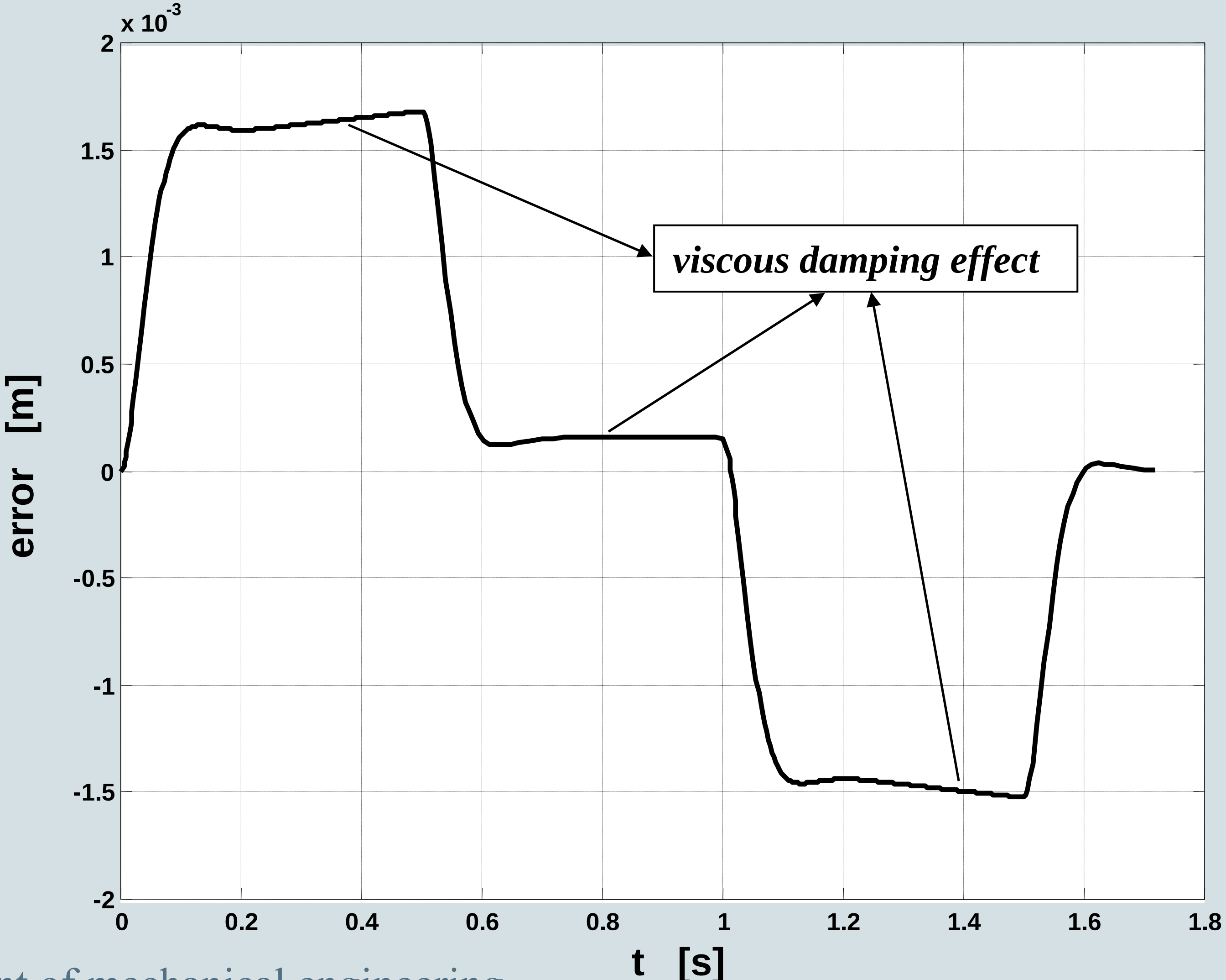
TU/e

Example: m=5 [kg], b=1 [Ns/m], 2nd degree setpoint



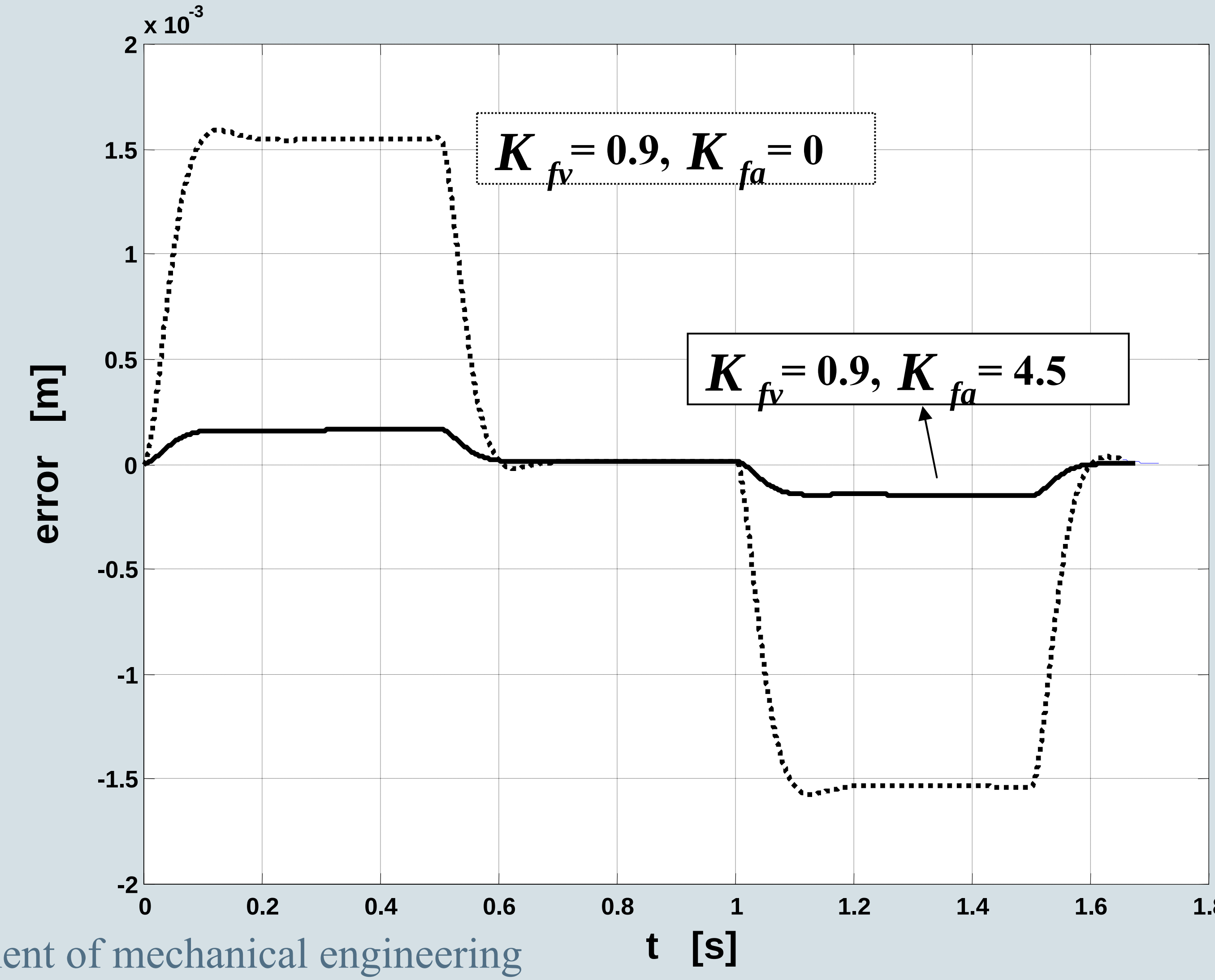
TU/e

Example: tracking error, no feedforward

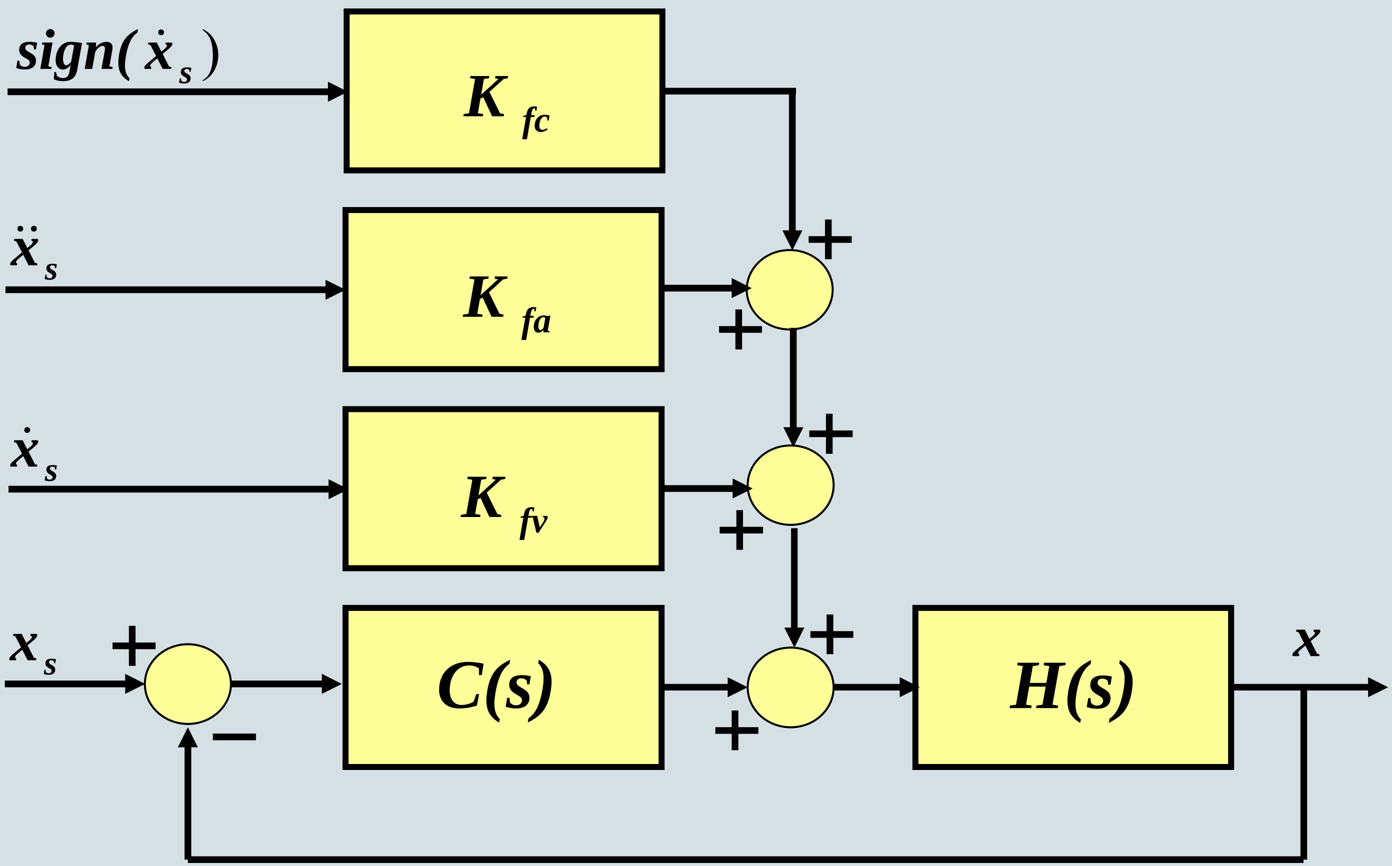


TU/e

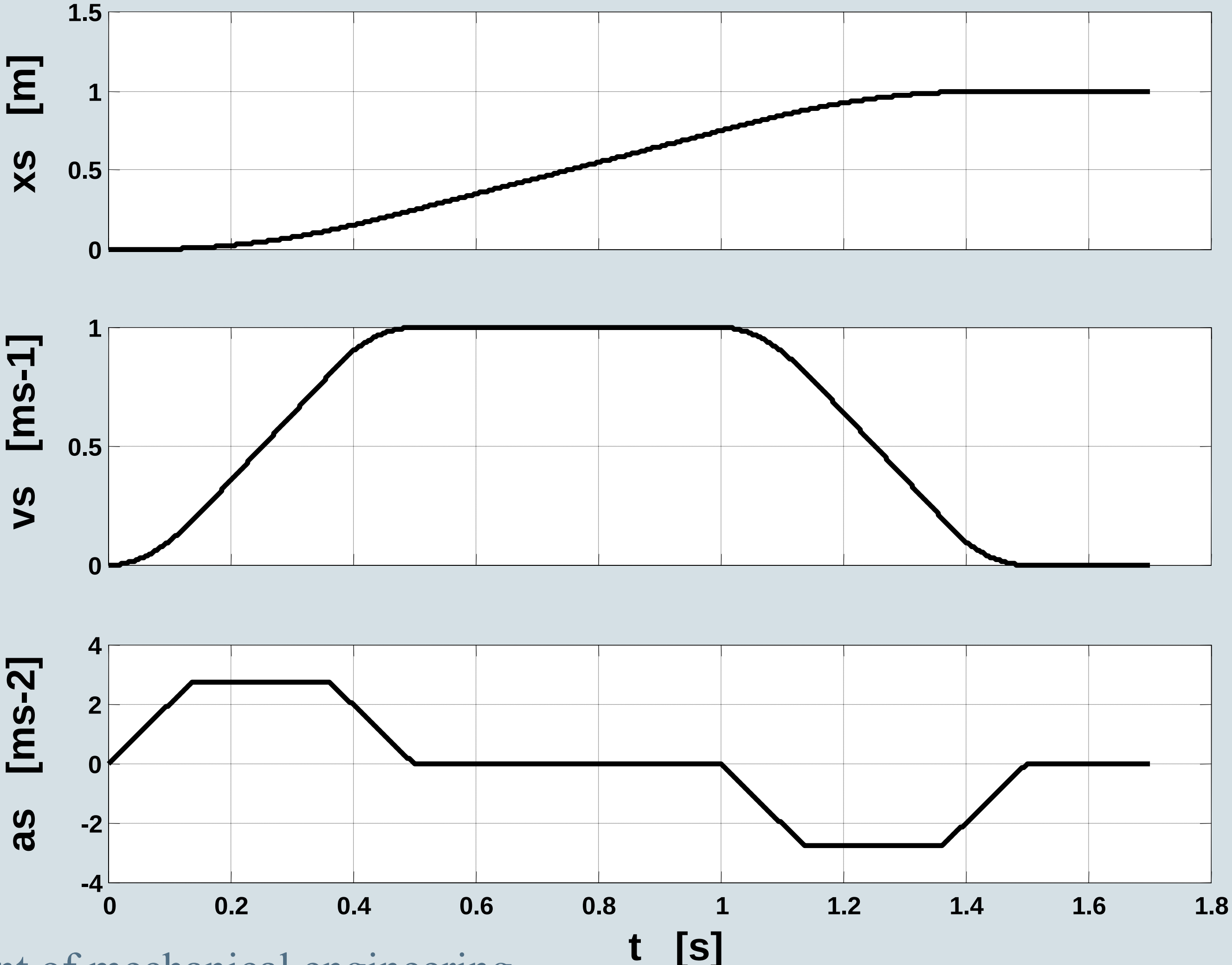
Example: tracking error, with feedforward



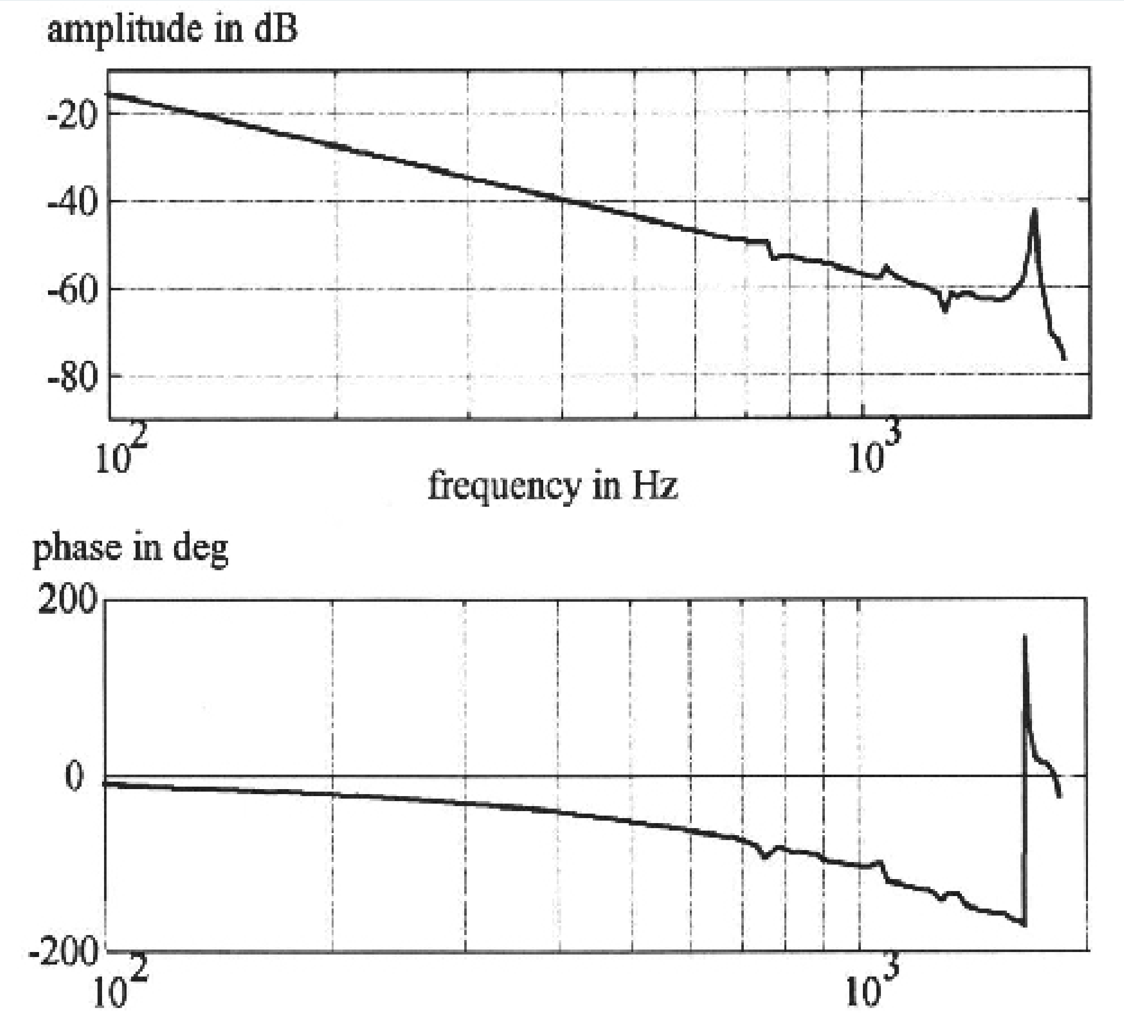
feedforward structure



3rd degree setpoint trajectory



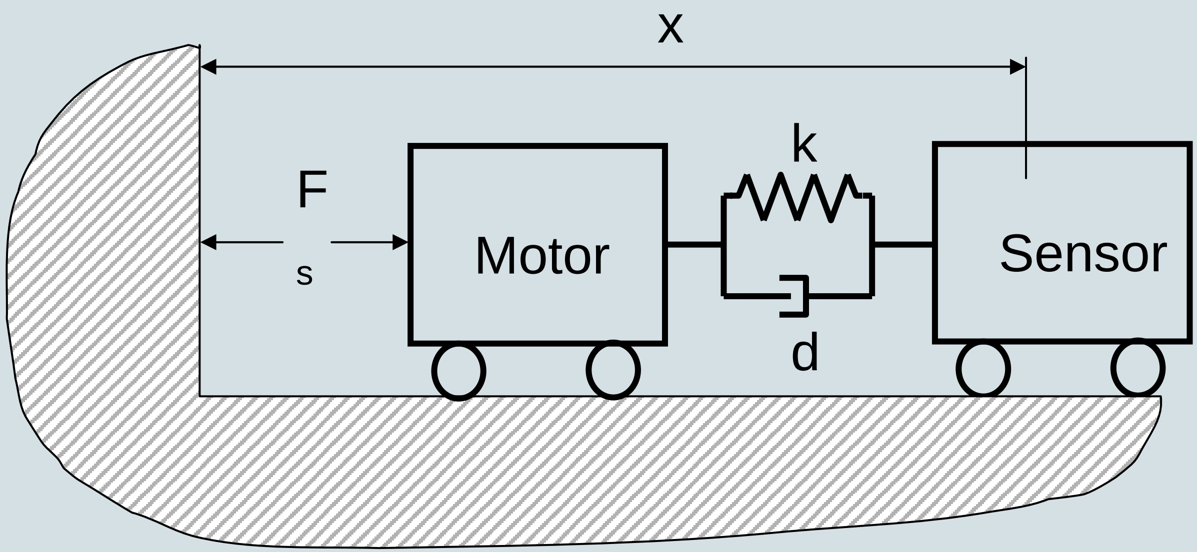
Parasitic Dynamics

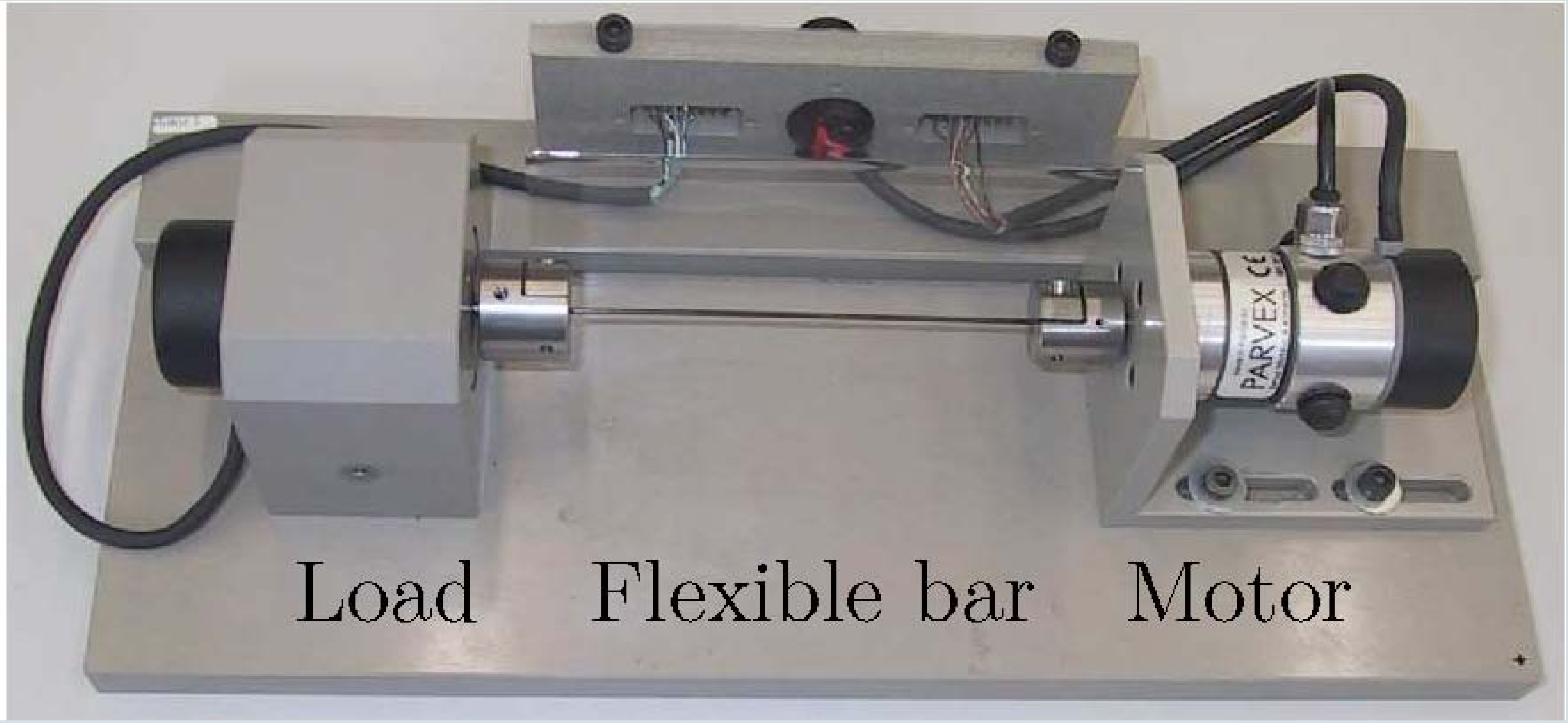

amplitude in dB
-20
-40
-60
-80
10^2
10^3
frequency in Hz
phase in deg
200
0
-200
10^2
10^3

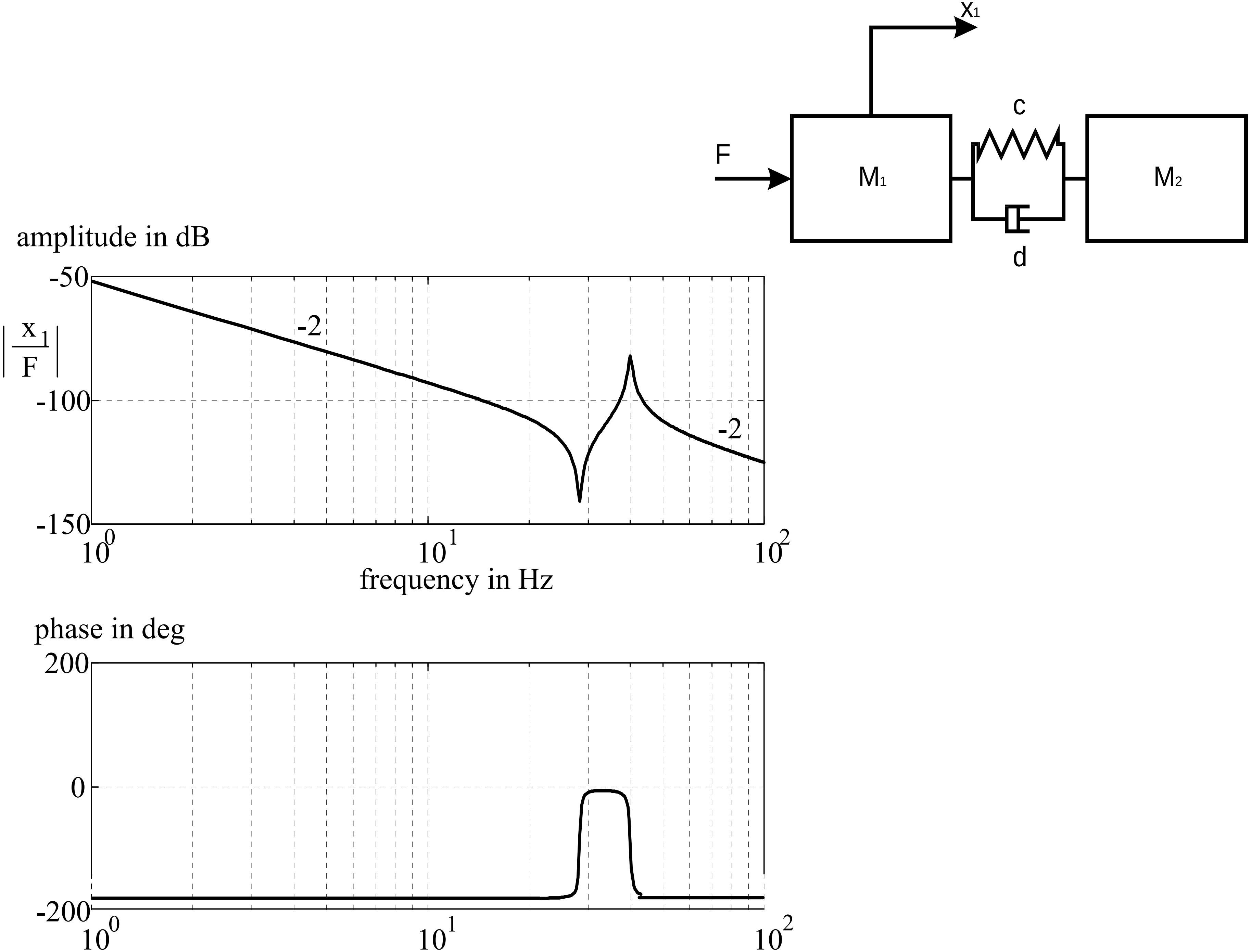
Three Types of Dynamic Effects

- Actuator flexibility
- Guidance flexibility
- Limited mass and stiffness of frame

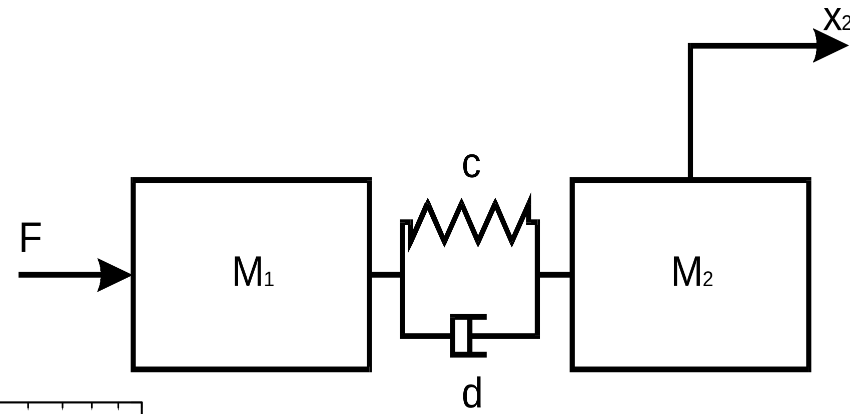
1. Actuator flexibility



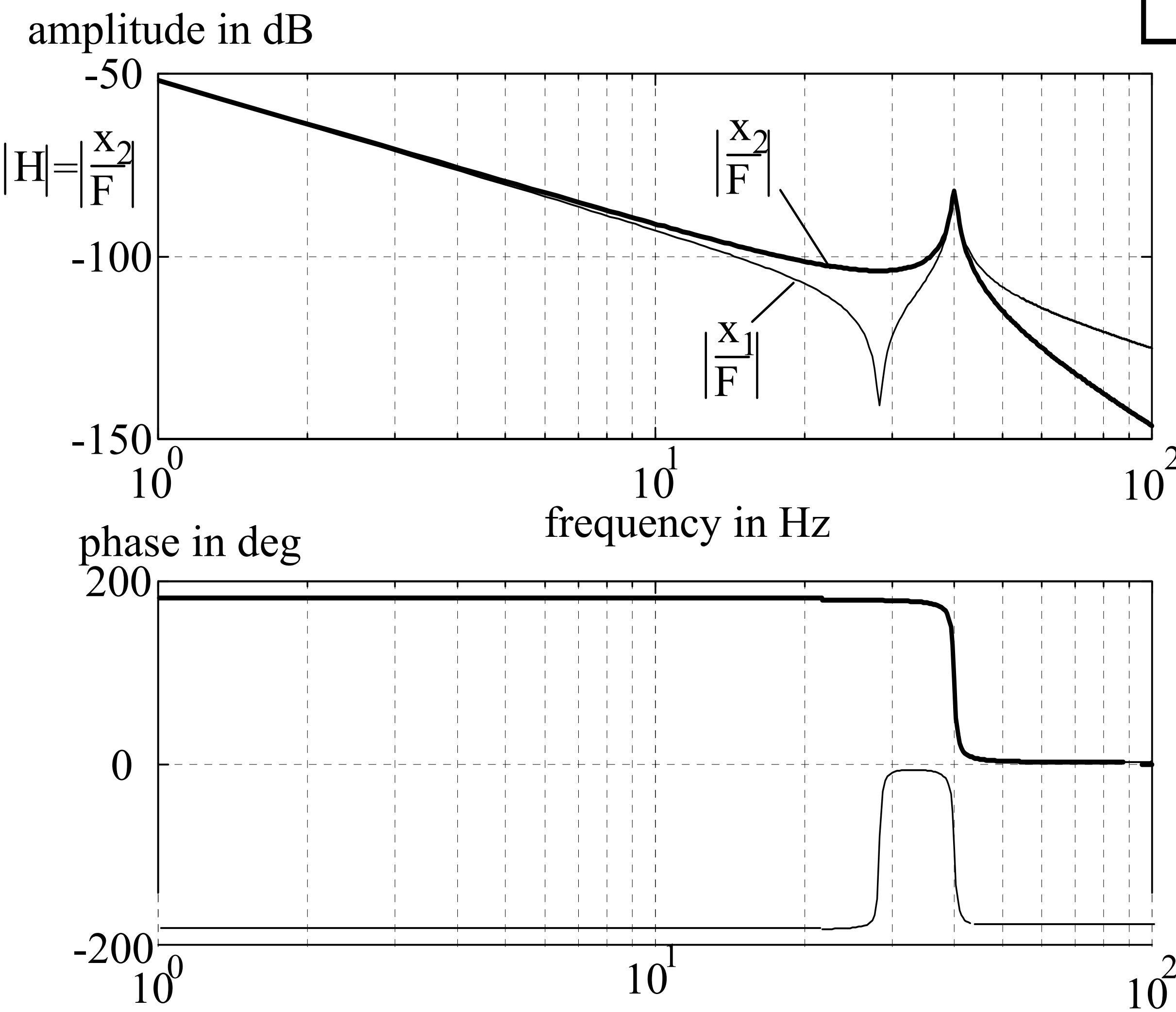

PARVEX
Load
Flexible bar
Motor



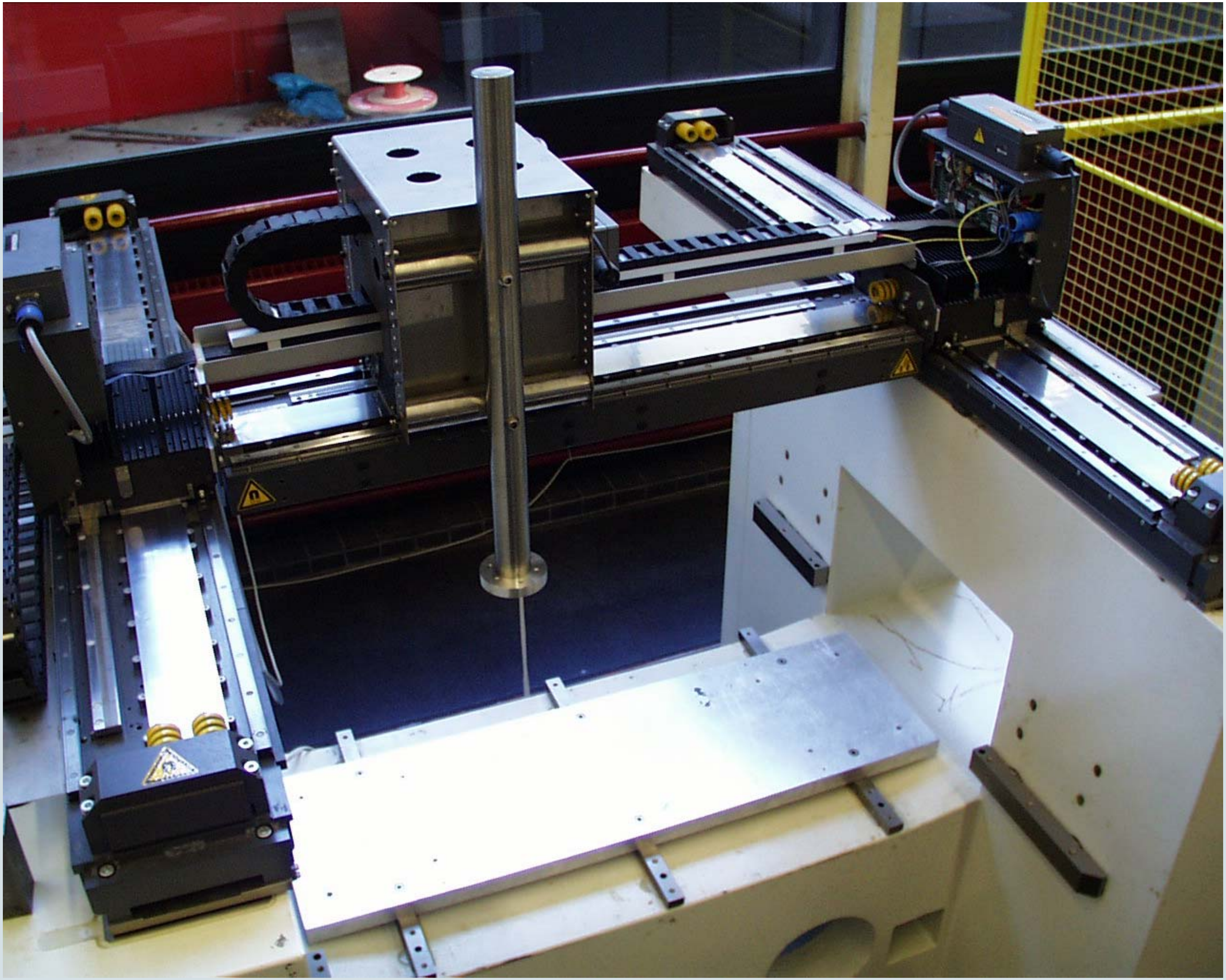
x1
F
M1
c
d
M2
amplitude in dB
-50
-100
-150
|x1/F|
-2
-2
10^0
10^1
10^2
frequency in Hz
phase in deg
200
0
-200
10^0
10^1
10^2

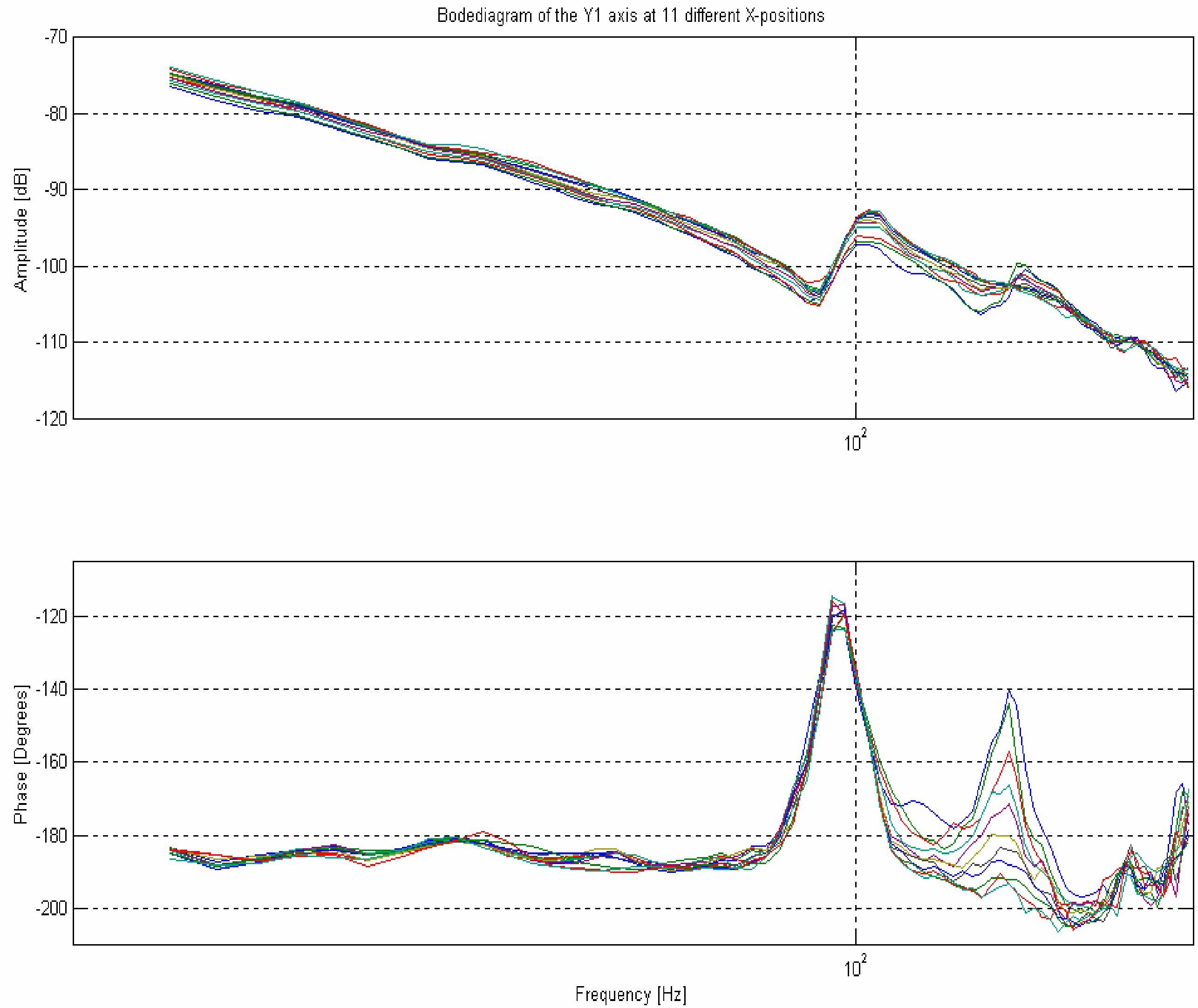


x2
c
F
M1
M2
d

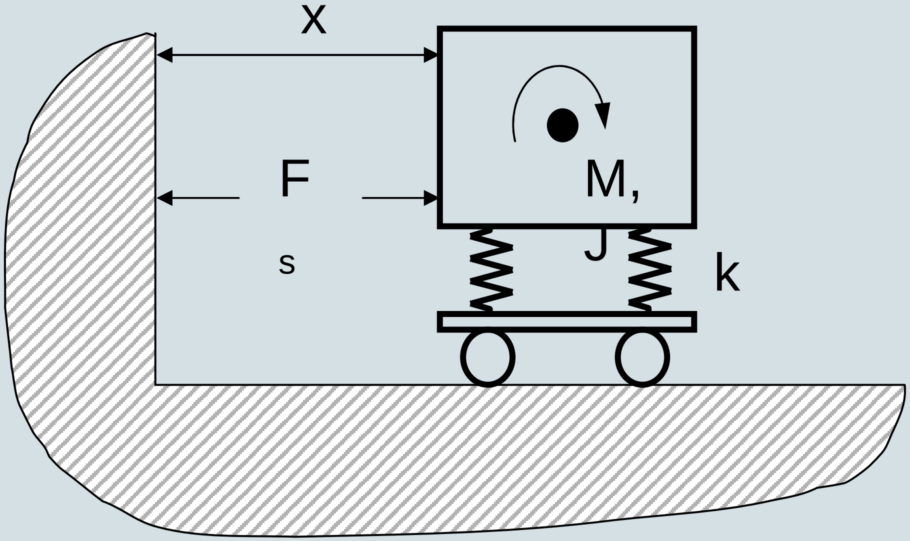


amplitude in dB
-50
-100
-150
|H|=|x2/F|
|x2/F|
|x1/F|
10^0
10^1
10^2
frequency in Hz
phase in deg
200
0
-200
10^0
10^1
10^2

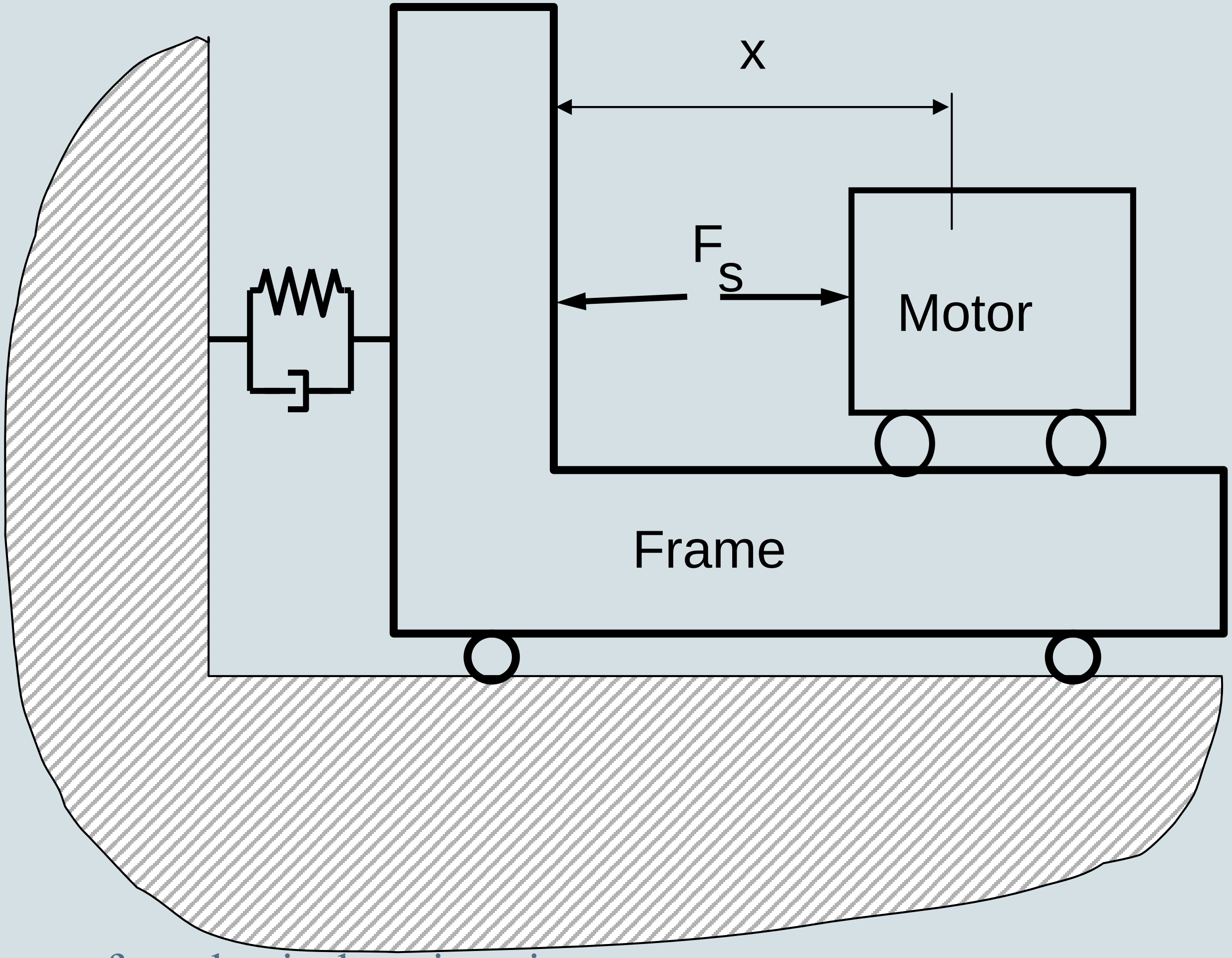



Bodediagram of the Y1 axis at 11 different X-positions
Amplitude [dB]
-70
-80
-90
-100
-110
-120
10^2
Phase [Degrees]
-120
-140
-160
-180
-200
10^2
Frequency [Hz]

2. Guidance flexibility



3. Limited mass and stiffness of frame

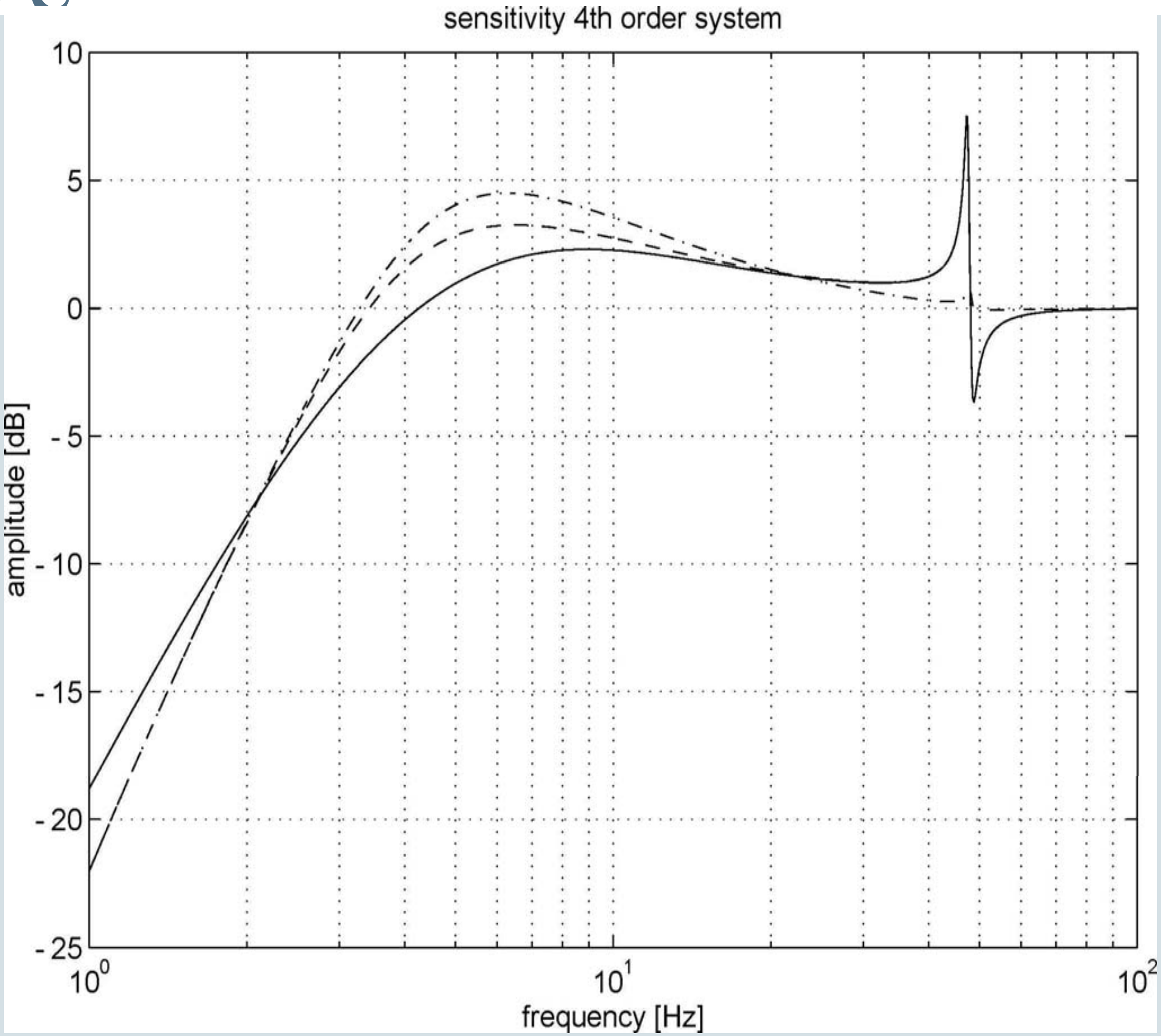


Motion Control Properties

- experimentation is ‘cheap’

  Disturbance Design Cycle: 7 min FRF measurement, model, loopshape, implementation
- plant decoupling, i.e. SISO
- feedforward: low-order model-based
- feedback: loopshaping
- key limitation: bode gain/phase - sensitivity integral

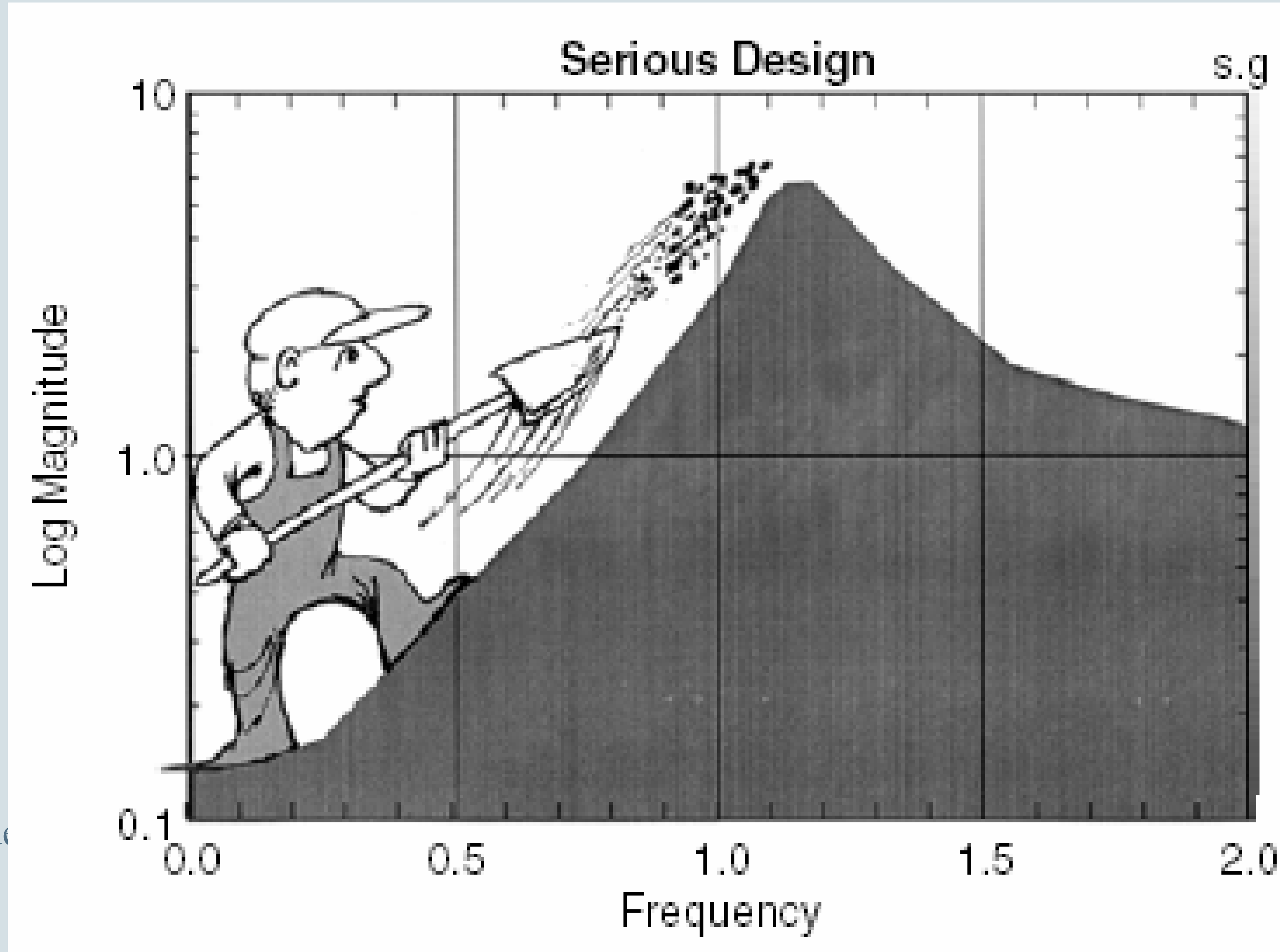
TU/e

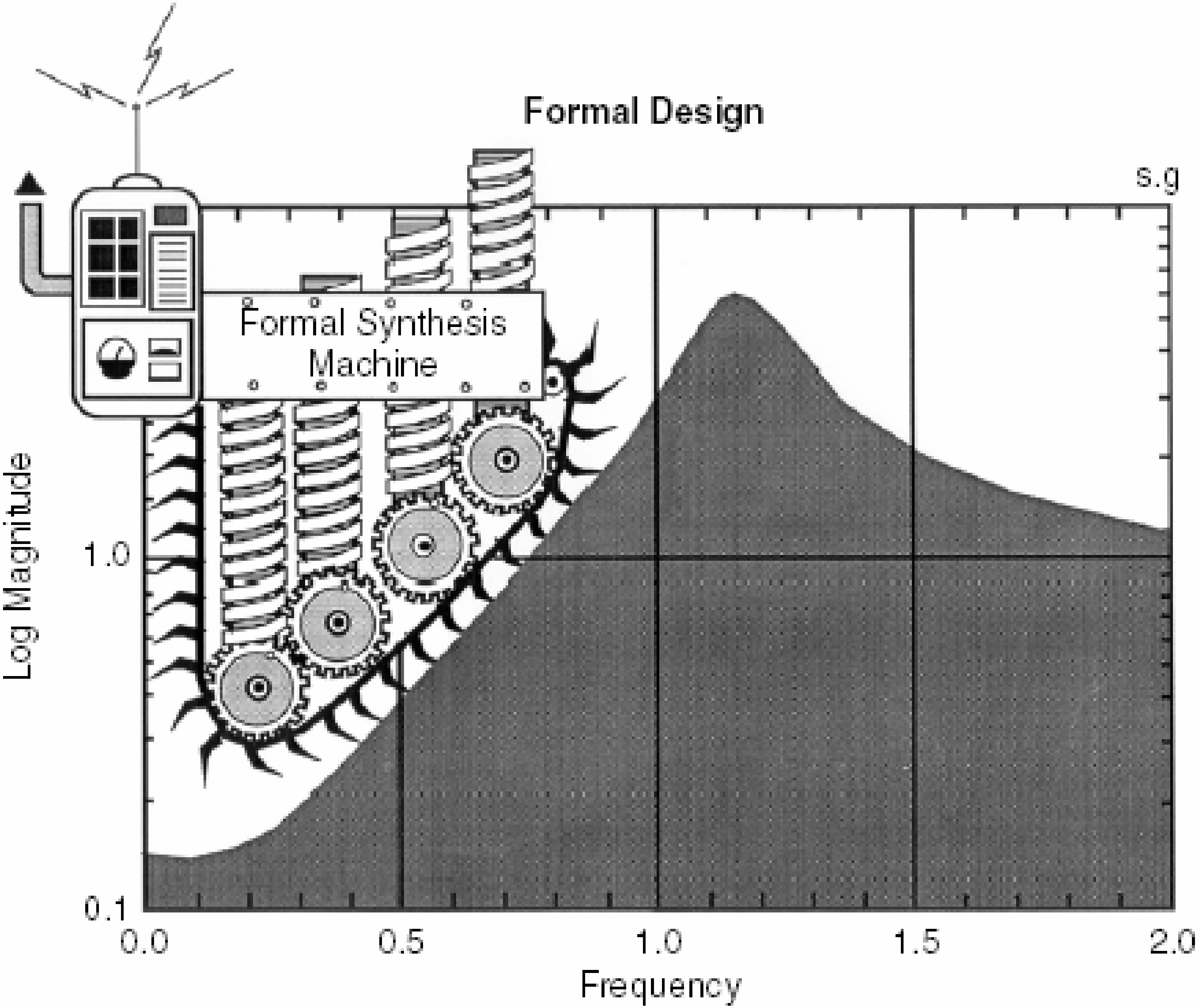


sensitivity 4th order system
amplitude [dB]
frequency [Hz]
10
5
0
- 5
- 10
- 15
- 20
- 25
10^0
10^1
10^2

Gunter Stein's Bode Lecture, CDC 1989

IEEE Control Systems Magazine, 23 (2003), pp 12- 25




Formal Design
s.g
Formal Synthesis
Machine
Log Magnitude
1.0
0.1
0.0
0.5
1.0
1.5
2.0
Frequency

Motion Control Challenge:

how to cope with Bode sensitivity limitation?

$$\int_0^\infty \log\left|S(j\omega)\right| d\omega = 0$$

directions of motion control research

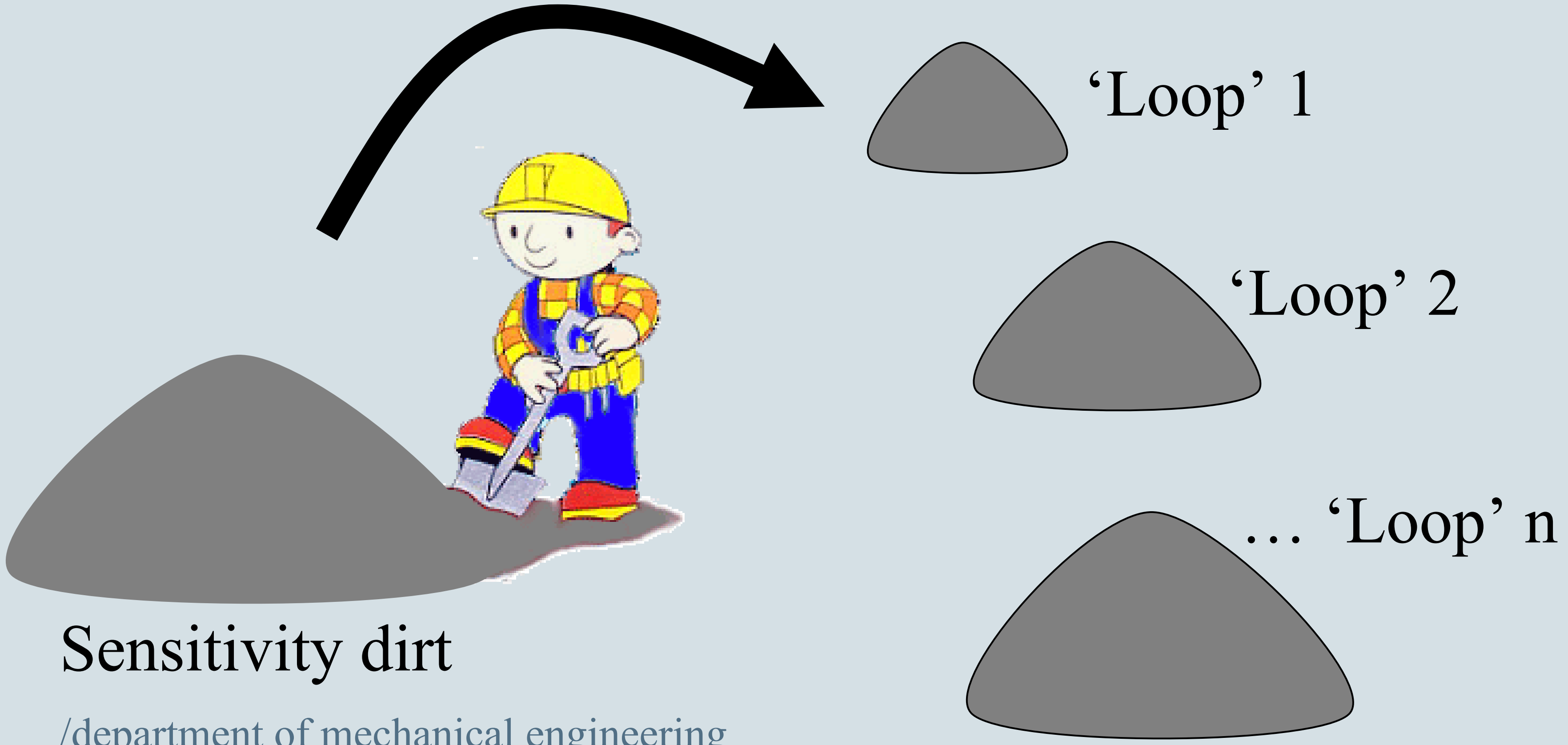
- MIMO loopshaping
- nonlinear control of linear systems (reset…)
- disturbance-based modelling and control
- data-driven control

directions of motion control research

- MIMO loopshaping
- nonlinear control of linear systems (reset…)
- disturbance-based modelling and control
- data-driven control

TU/e

MIMO integral constraints…



/department of mechanical engineering

directions of motion control research

- MIMO loopshaping
- nonlinear control of linear systems (reset…)
- disturbance-based modelling and control
- data-driven control

Problem formulation

- Do there exist nonlinear feedback controllers that give better ‘performance’ for linear motion systems than linear solutions?

Approach

- Performance measures?
- Plant is linear, but
- disturbances and specifications ‘change’
- Use LPV for synthesis?
- How about non-smooth (reset) filters

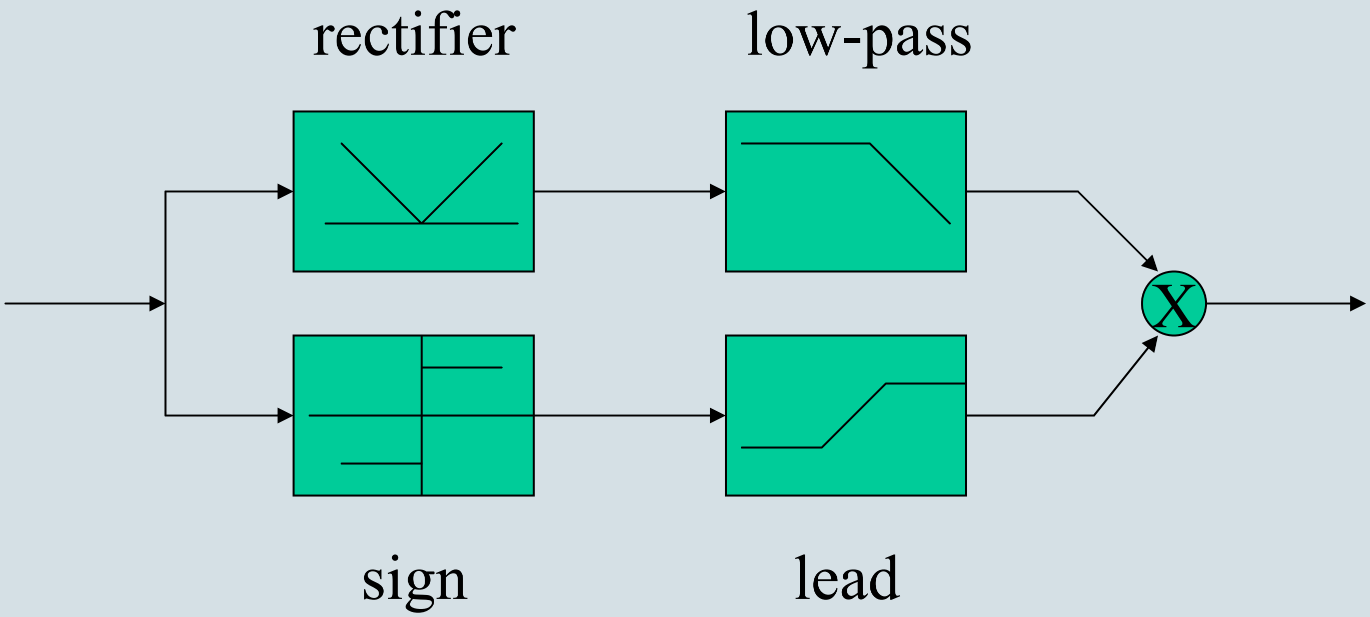
Bode Gain/Phase relation

Slope = n

means

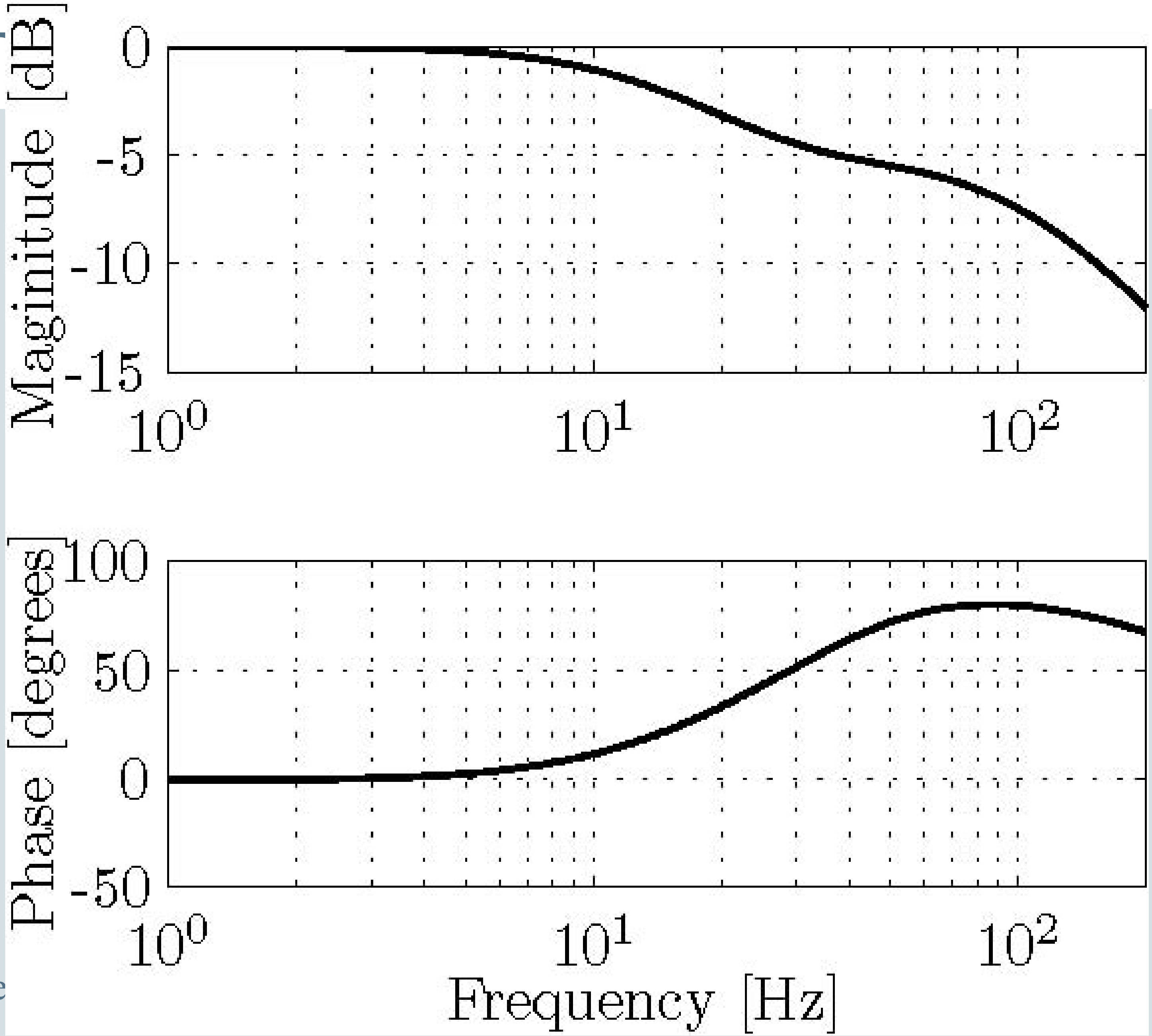
phase = n*90 degrees

SPAN- filter

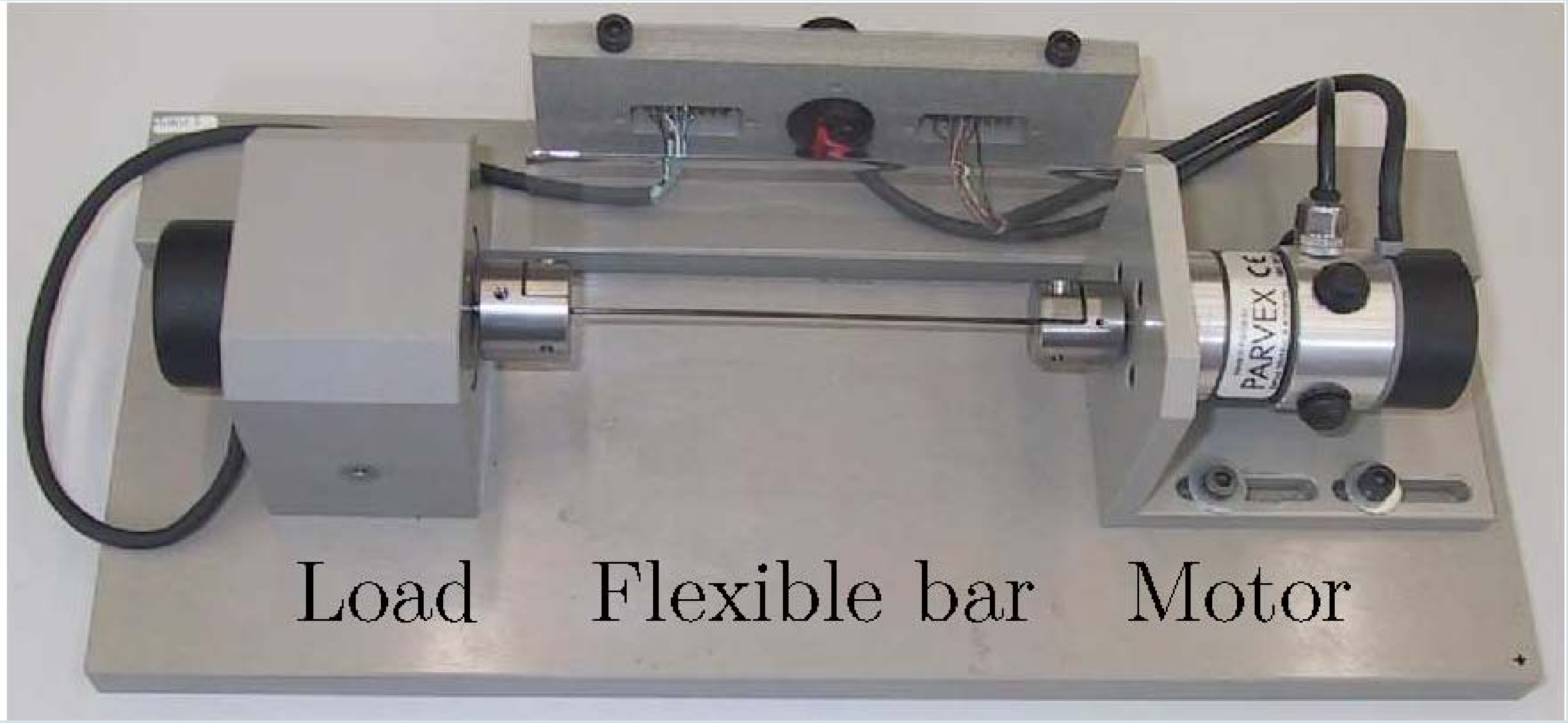


be creative with control!

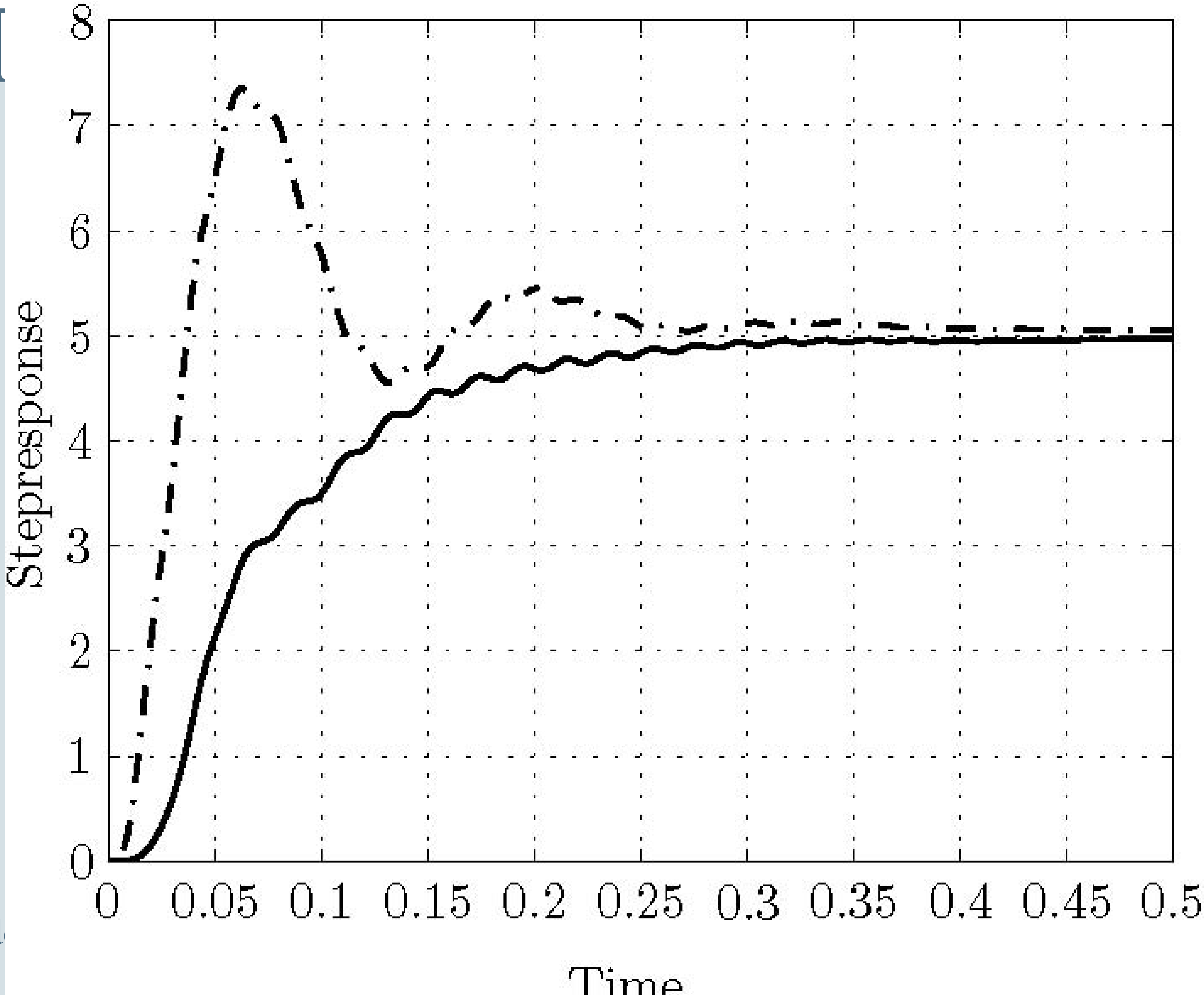
T


Maginitude [dB]
0
-5
-10
-15
10^0
10^1
10^2
Phase [degrees]
100
50
0
-50
10^0
10^1
10^2
Frequency [Hz]

/de


Load
Flexible bar
Motor
PARVEX

T


8
7
6
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Stepresponse
Time

/d

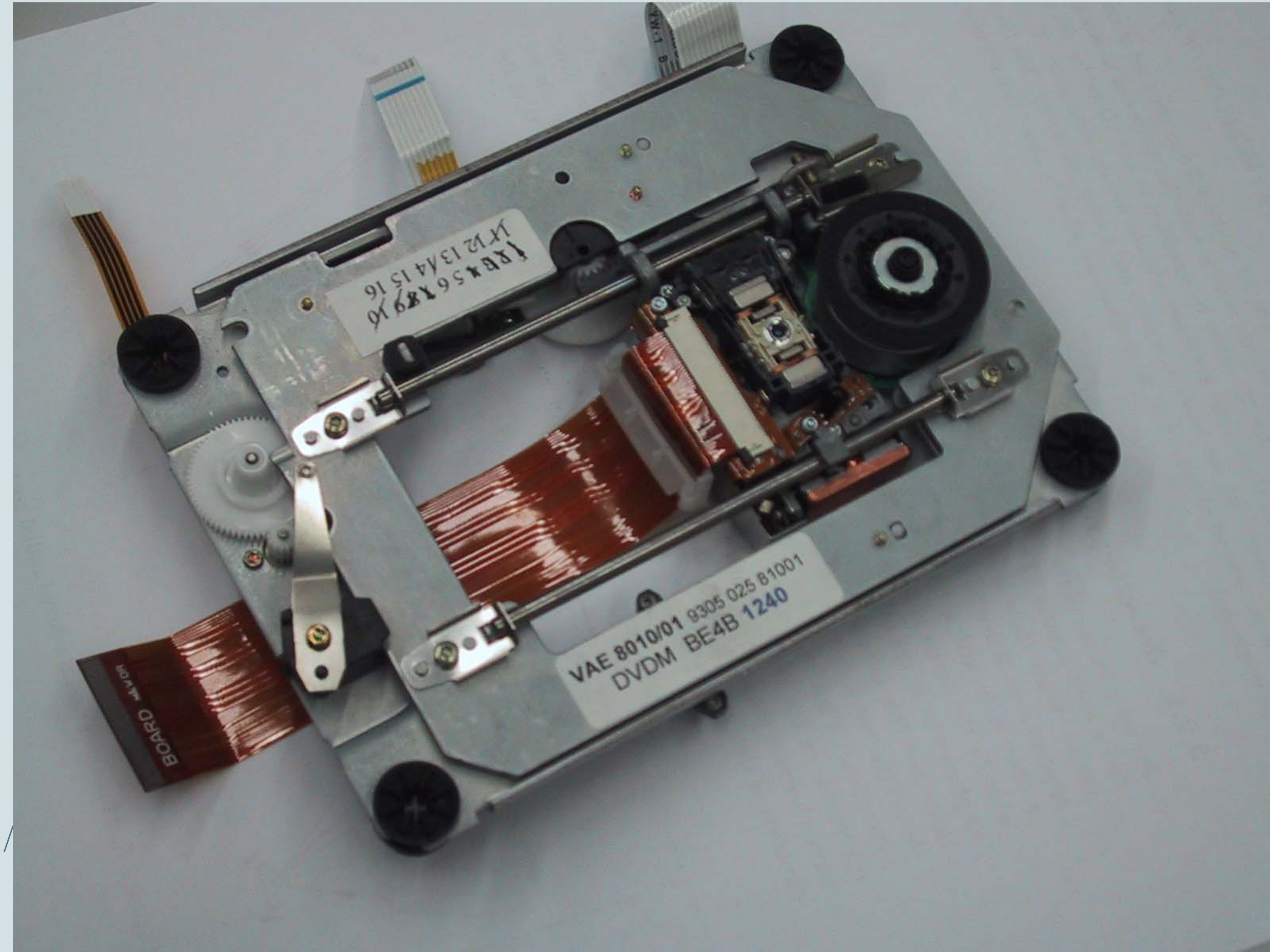
directions of motion control research

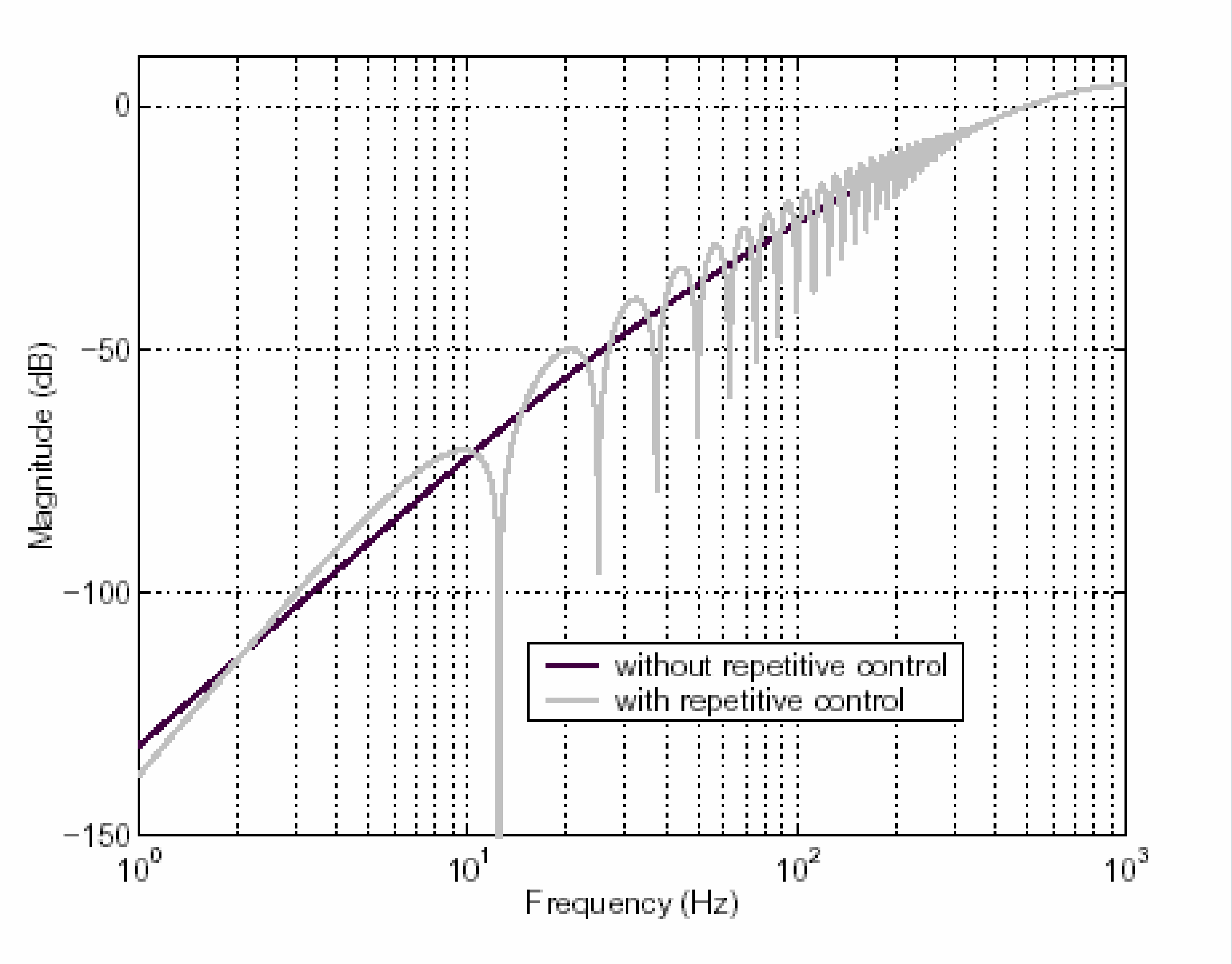
- MIMO loopshaping
- nonlinear control of linear systems (reset…)
- disturbance-based modelling and control
- data-driven control

disturbance-based modelling and control

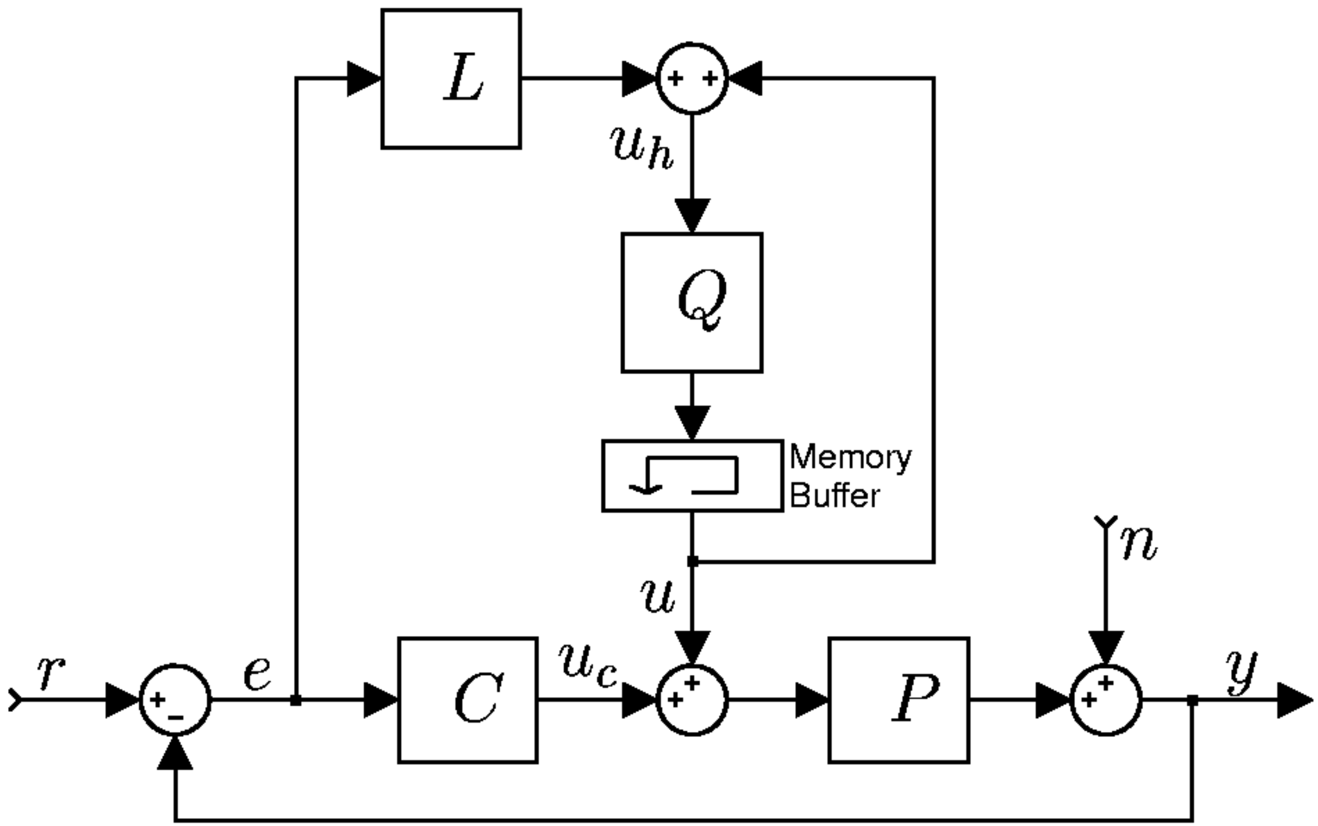
- disc errors vs shocks optical storage
- stochastic vs deterministic disturbances
- repetitive vs a-periodic setpoints or disturbances

Internal model principle….

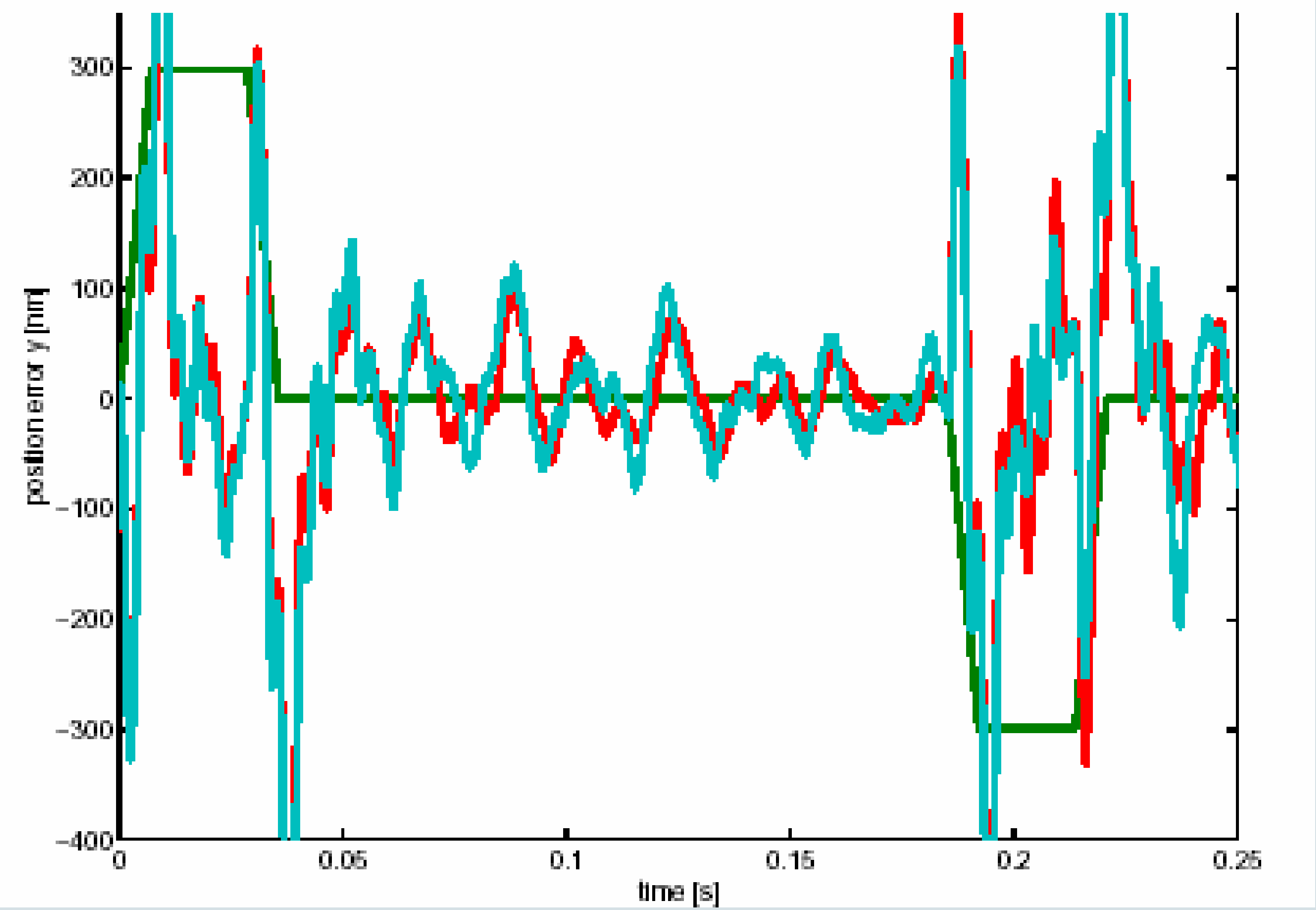

VAE 8010/01 9305 025 81001
DVDM BE4B 1240
BOARD

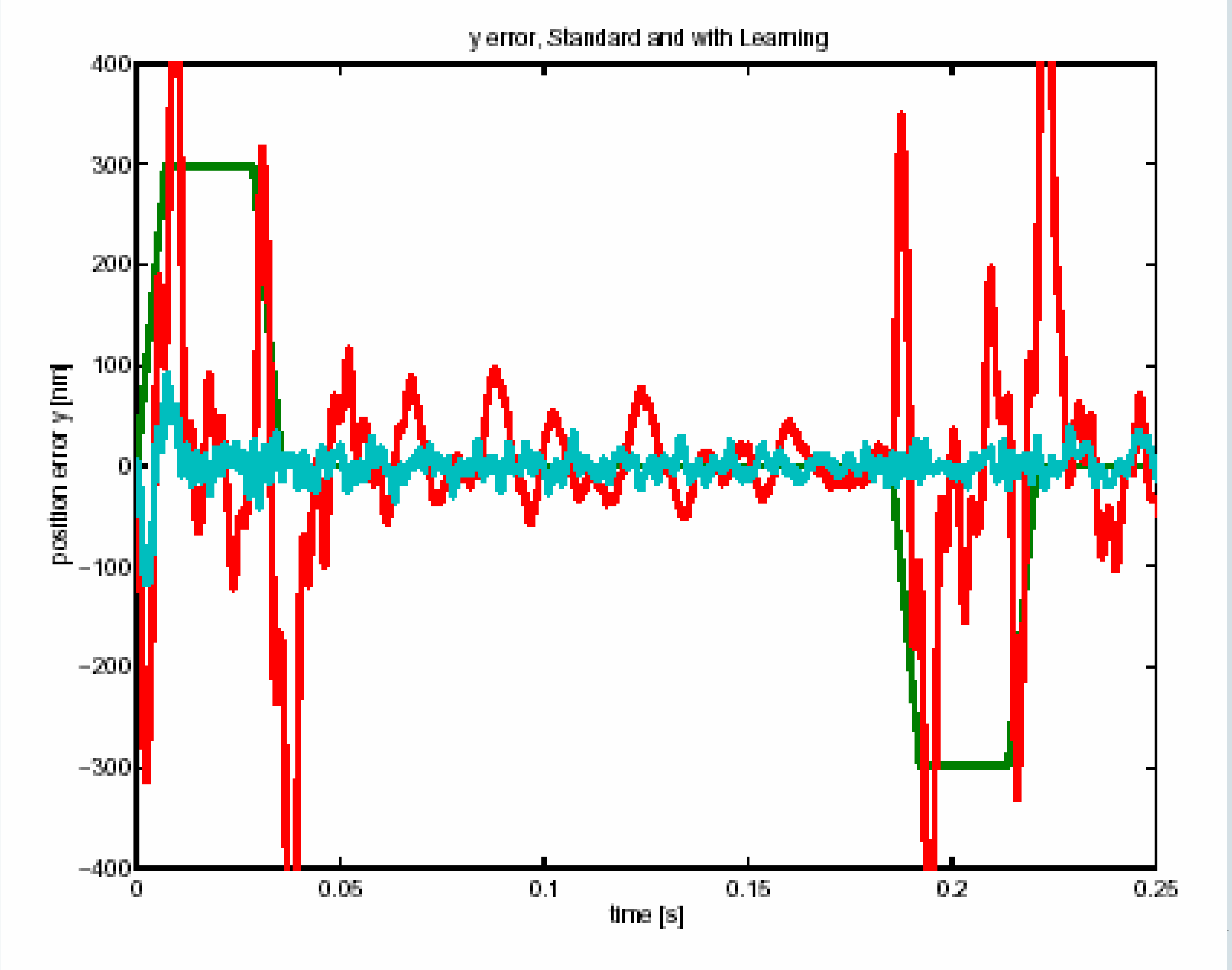

0
−50
−100
−150
Magnitude (dB)
10^0
10^1
10^2
10^3
Frequency (Hz)
without repetitive control
with repetitive control

Iterative Learning Control (ILC)



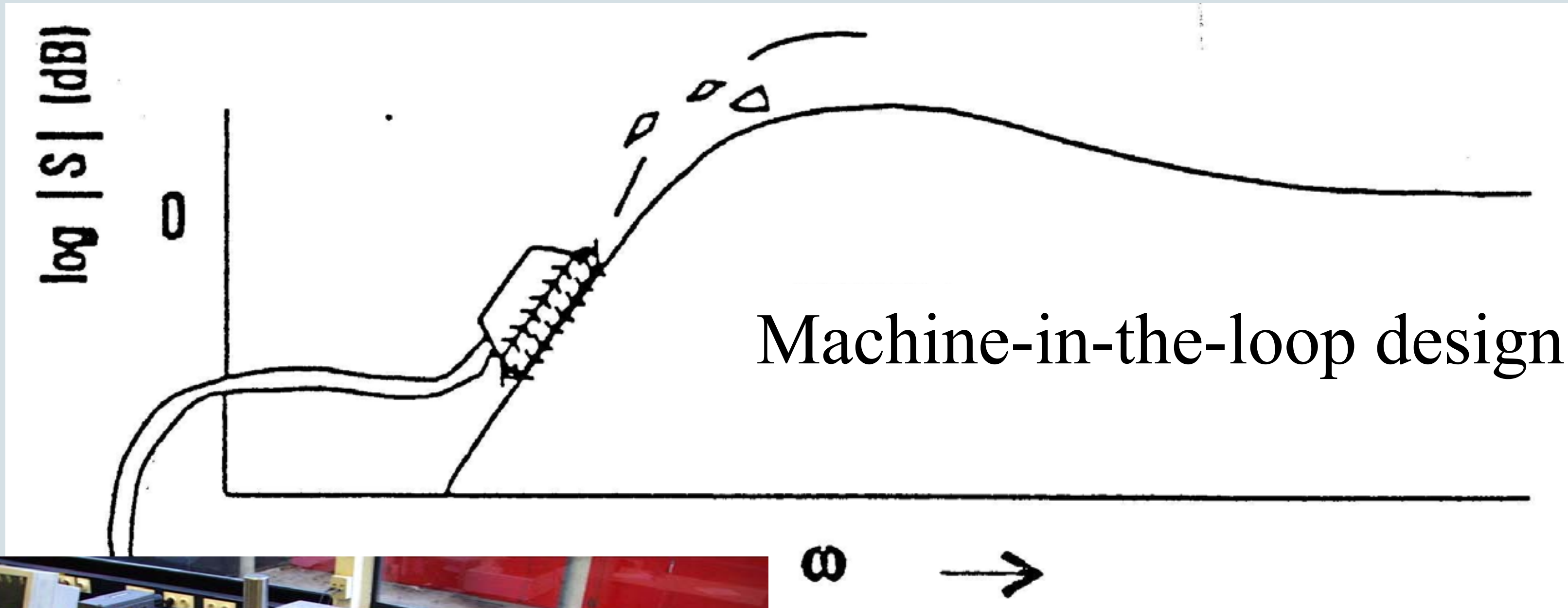
$$e_{k+1} < e_k \longleftarrow \left| Q\left(1 - L\,PS\right) \right| < 1$$


300
200
100
0
−100
−200
−300
−400
0
0.05
0.1
0.15
0.2
0.25
time [s]
position error y [nm]

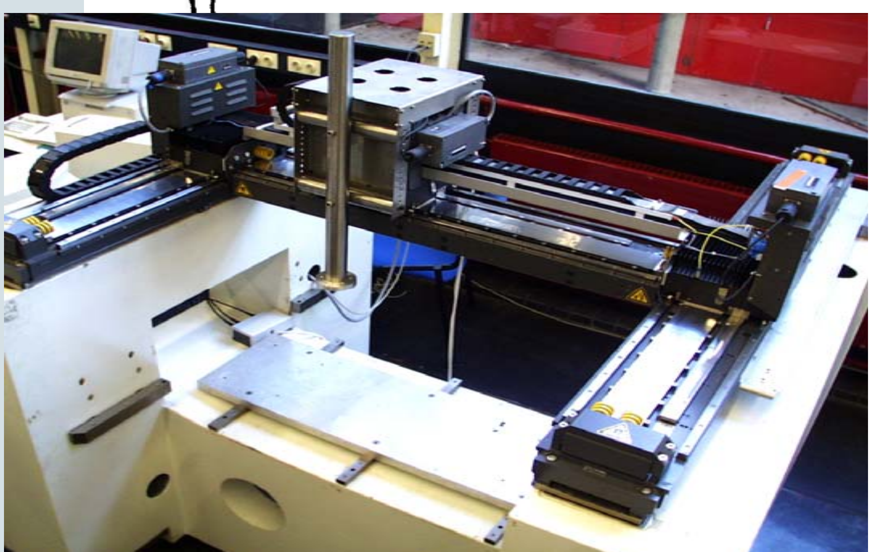

y error, Standard and with Learning
position error y [nm]
400
300
200
100
0
−100
−200
−300
−400
0
0.05
0.1
0.15
0.2
0.25
time [s]

directions of motion control research

- MIMO loopshaping
- nonlinear control of linear systems (reset…)
- disturbance-based modelling and control
- data-driven control



Machine-in-the-loop design

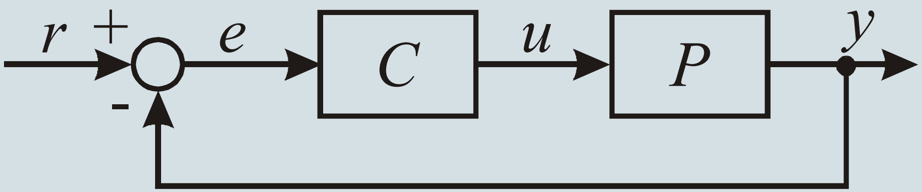


Data-driven control

- Examples:
  - *data-based LQG control*
  - *iterative feedback tuning*
  - *virtual reference feedback tuning*
  - *unfalsified control*

Problem statement

- Design a SISO LTI controller *C* for LTI plant *P*



- Control objective: realize the desired S_o and T_o
- Ideal controller C_o:

$$S_o = \frac{1}{1+PC_o}, \quad T_o = \frac{PC_o}{1+PC_o}.$$

Data-based controller design

- The controller class: $\{C(z,\boldsymbol{\theta})\} = \{C_p(z)\boldsymbol{\beta}^T(z)\boldsymbol{\theta}\}.$

- $C_p(z)$ is directly prescribed by the designer: notches, integrators, etc.
- Basis functions: $\boldsymbol{\beta}(z) = [\beta_0(z)\ \beta_1(z)\ \ldots\ \beta_n(z)]^T.$

- Tuning parameters: $\boldsymbol{\theta} = [\theta_0\ \theta_1\ \ldots \theta_n]^T.$

- Constraint on C_o: $T_o(z) = C_o(z)S_o(z)P(z)$

- Model-based cost function:

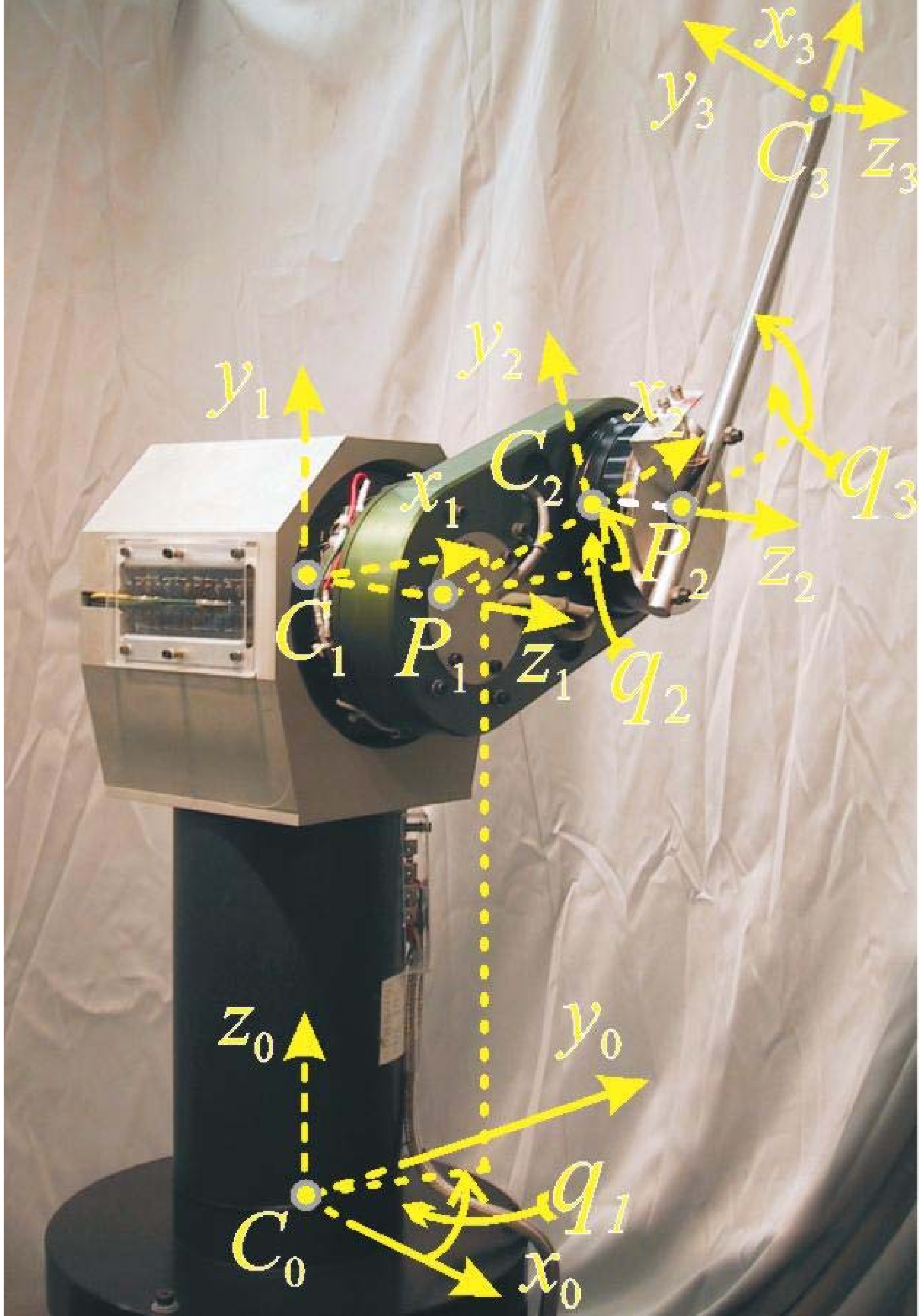
$$J_{MB}(\boldsymbol{\theta}) = \left\| \left(T_o(z) - C(z,\boldsymbol{\theta})S_o(z)P(z) \right) W(z) \right\|_2^2$$

- Processing the measurements:

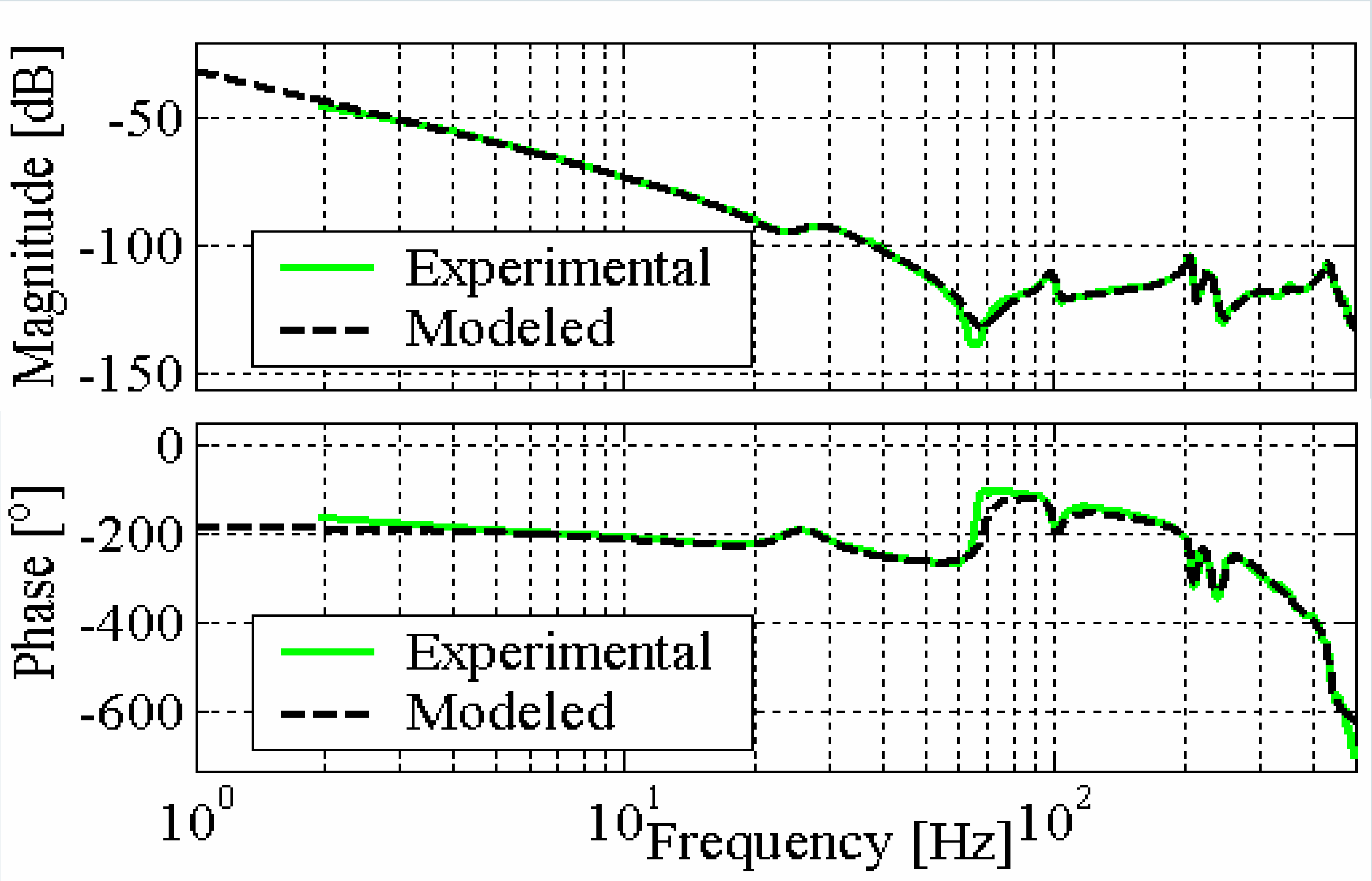
$$T_o(z)u(t) = C(z,\boldsymbol{\theta})S_o(z)P(z)u(t) \;\Rightarrow\; T_o(z)u(t) = C(z,\boldsymbol{\theta})S_o(z)y(t)$$

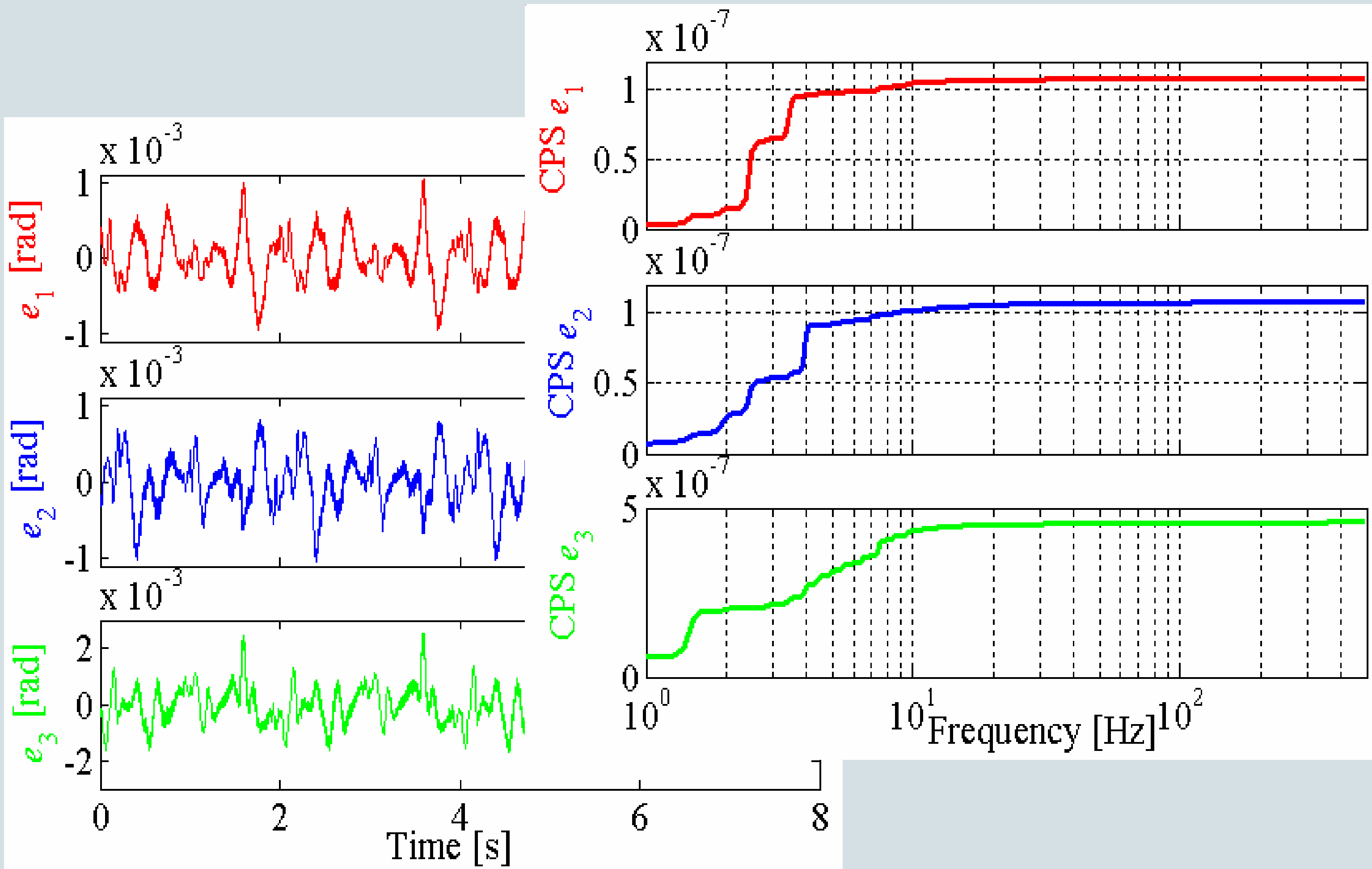
- Data-based cost function:

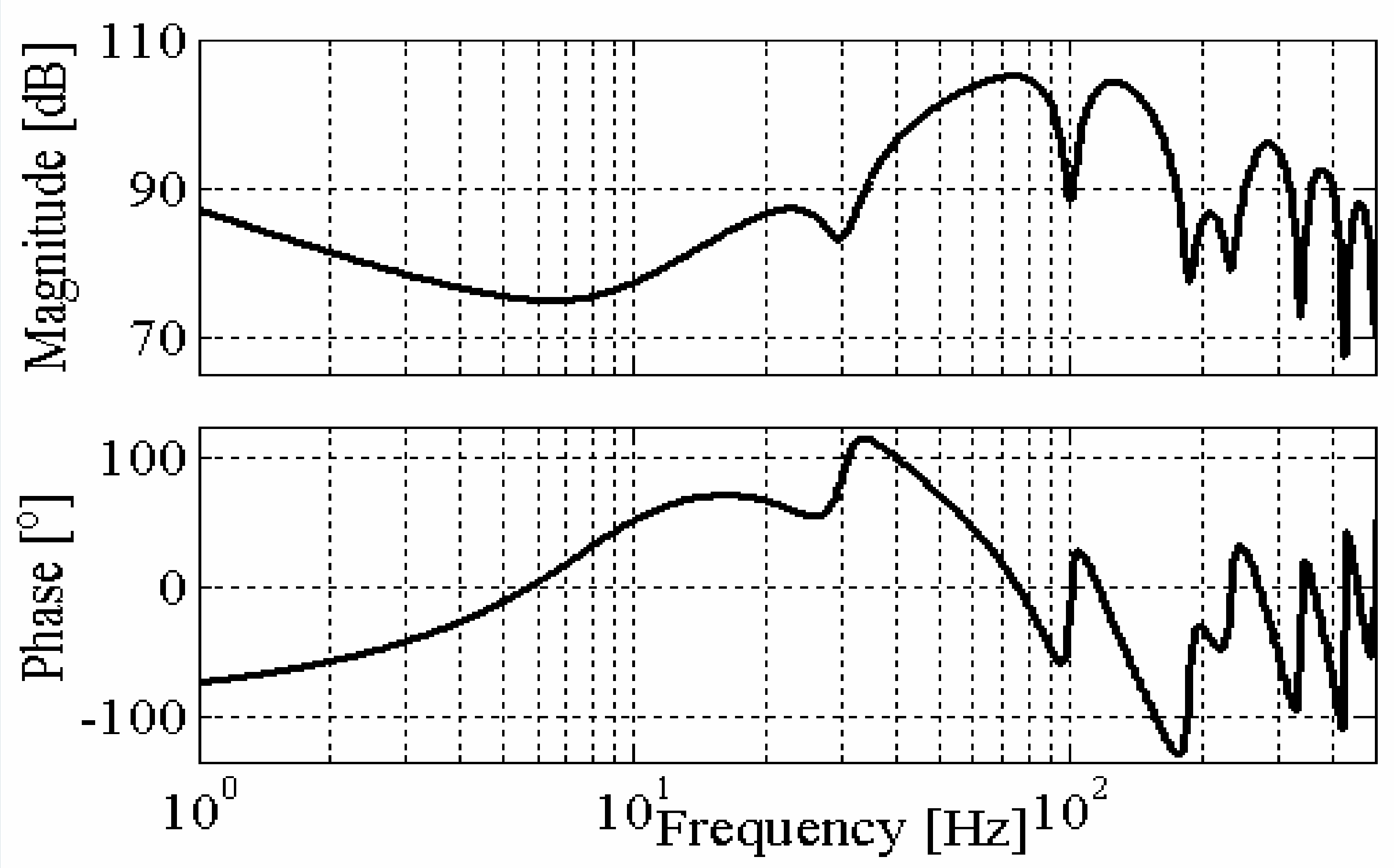
$$J_{DB}^N(\boldsymbol{\theta}) = \frac{1}{N}\sum_{t=1}^{N}\left[L(z)\left(T_o(z)u(t) - C(z,\boldsymbol{\theta})S_o(z)y(t)\right)\right]^2$$



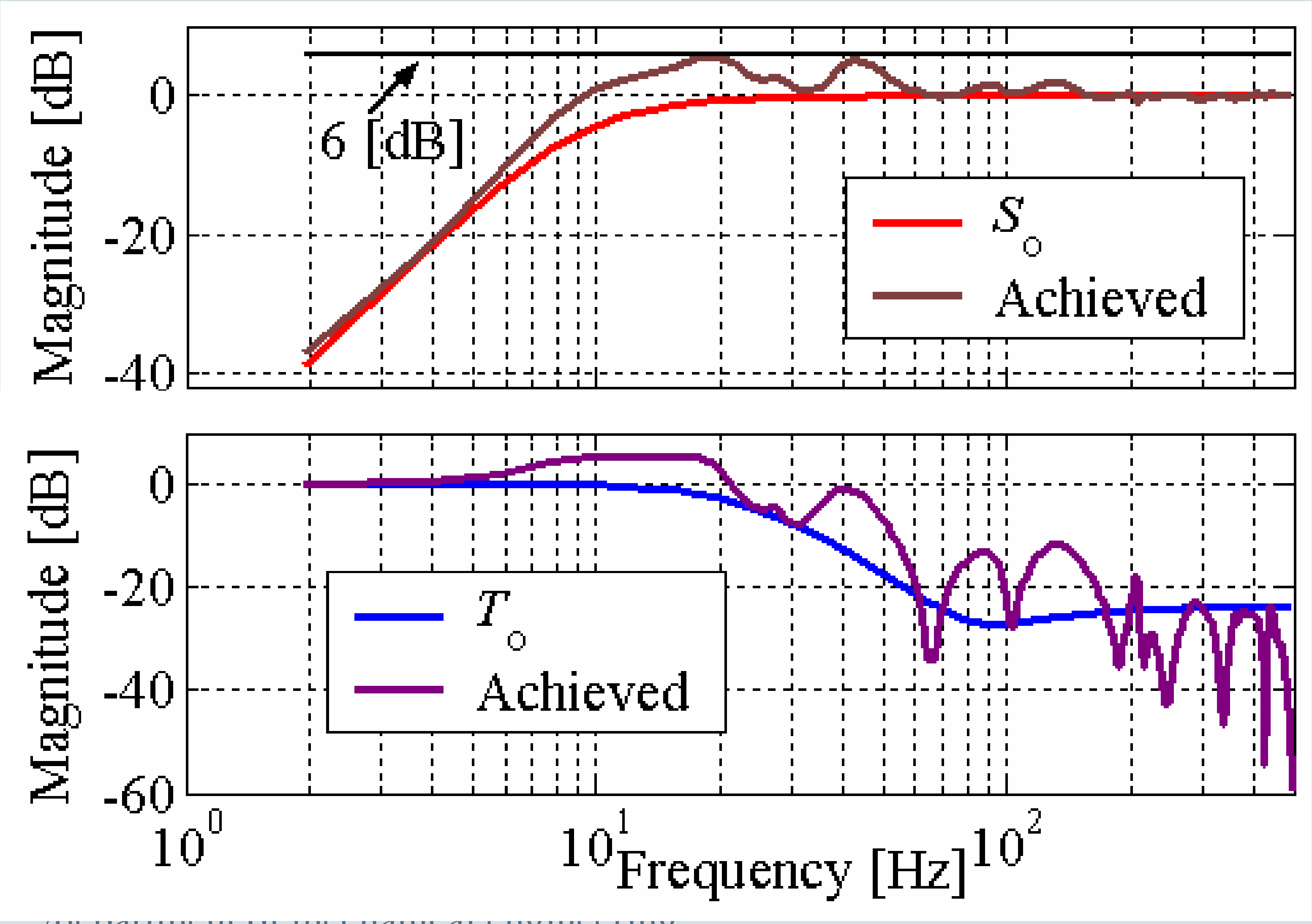
x3
y3
C3
z3
y2
y1
C2
x1
q3
P2
z2
C1
P1
z1
q2
z0
y0
C0
q1
x0


Magnitude [dB]
-50
-100
-150
Experimental
Modeled
Phase [°]
0
-200
-400
-600
Experimental
Modeled
10^0
10^1
10^2
Frequency [Hz]


x 10^-3
1
0
-1
e1 [rad]
x 10^-3
1
0
-1
e2 [rad]
x 10^-3
2
0
-2
e3 [rad]
0
2
4
6
8
Time [s]
x 10^-7
1
0.5
0
CPS e1
x 10^-7
1
0.5
0
CPS e2
x 10^-7
5
0
CPS e3
10^0
10^1
10^2
Frequency [Hz]



$$C_1(z, \hat{\boldsymbol{\theta}}_{\mathrm{DB}}^{N})$$

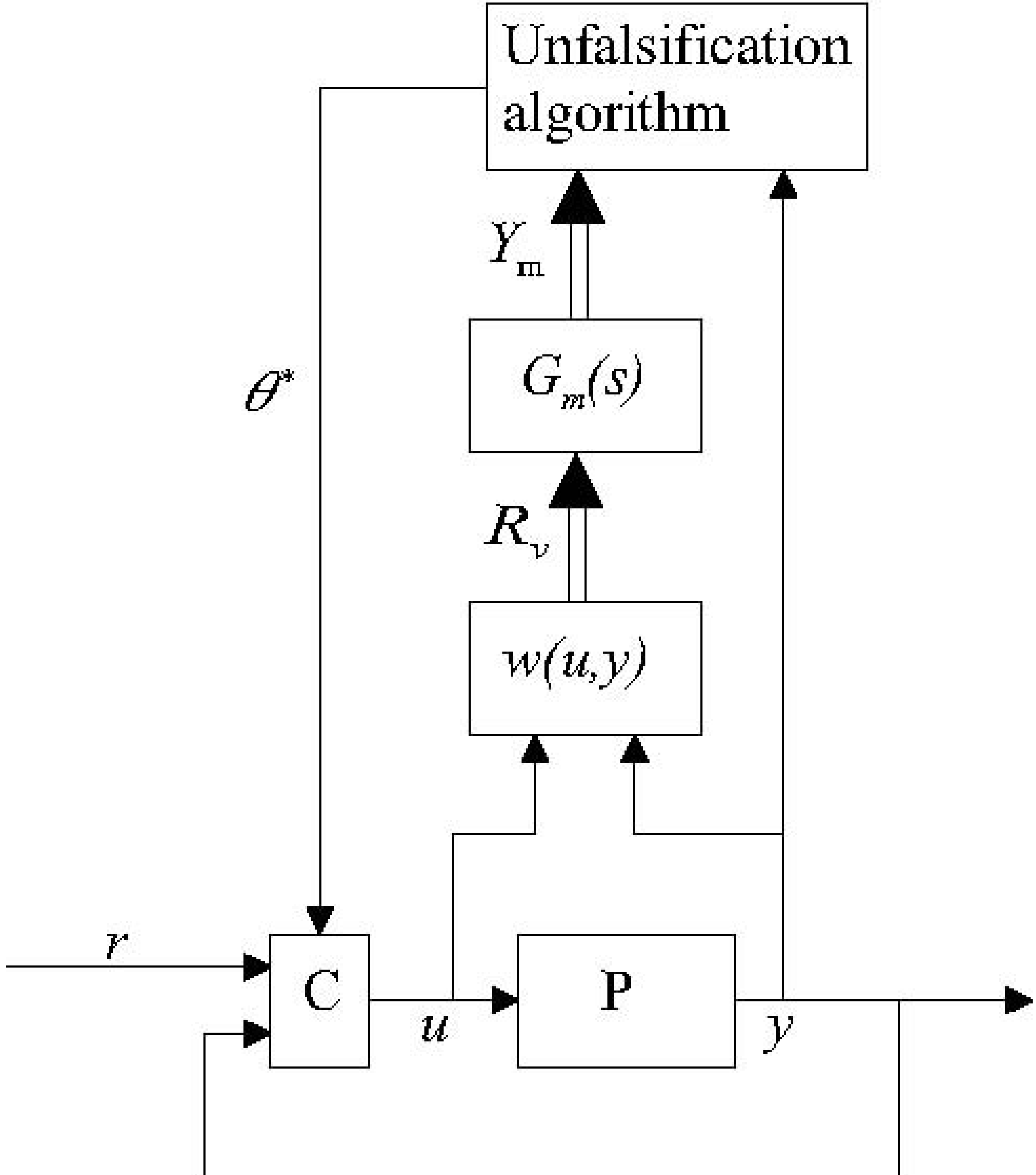


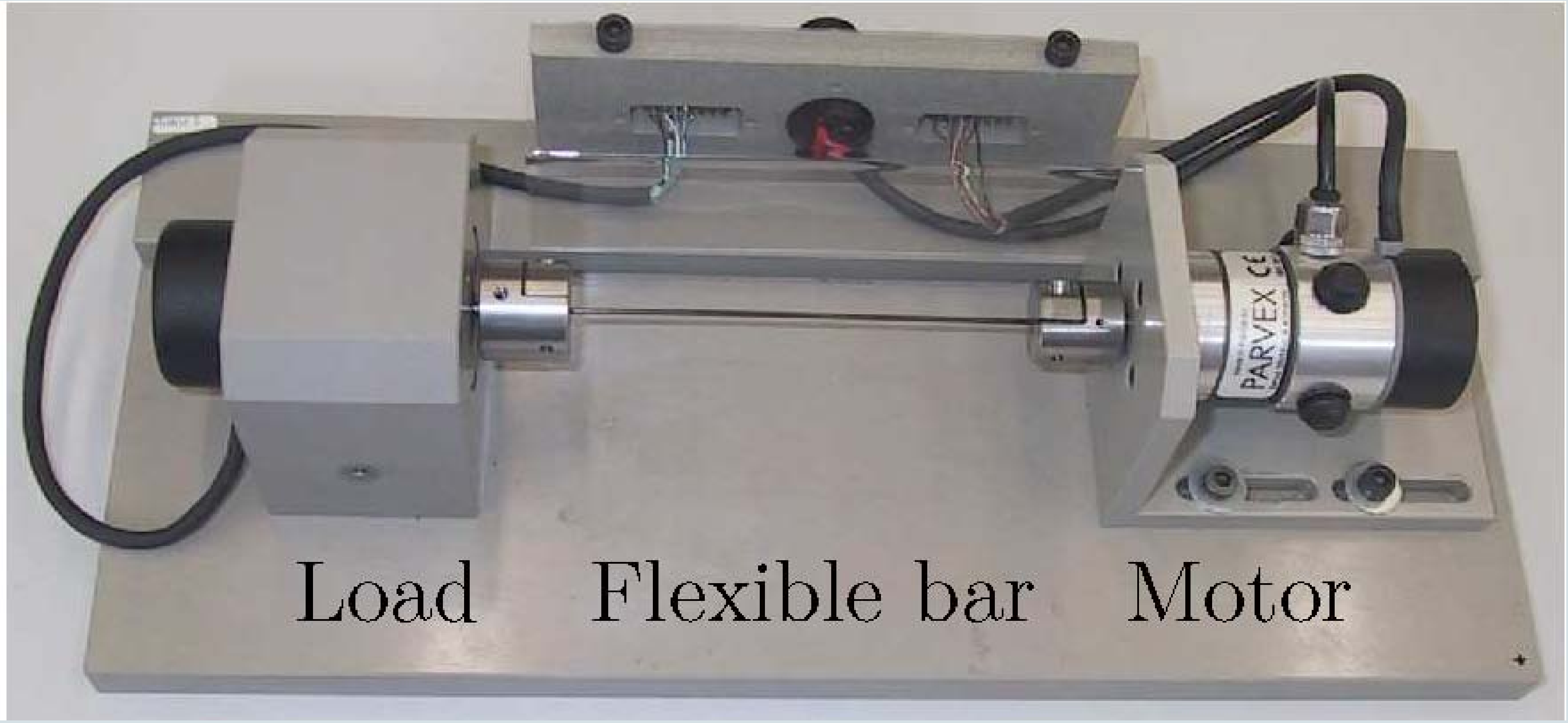
/department of mechanical engineering

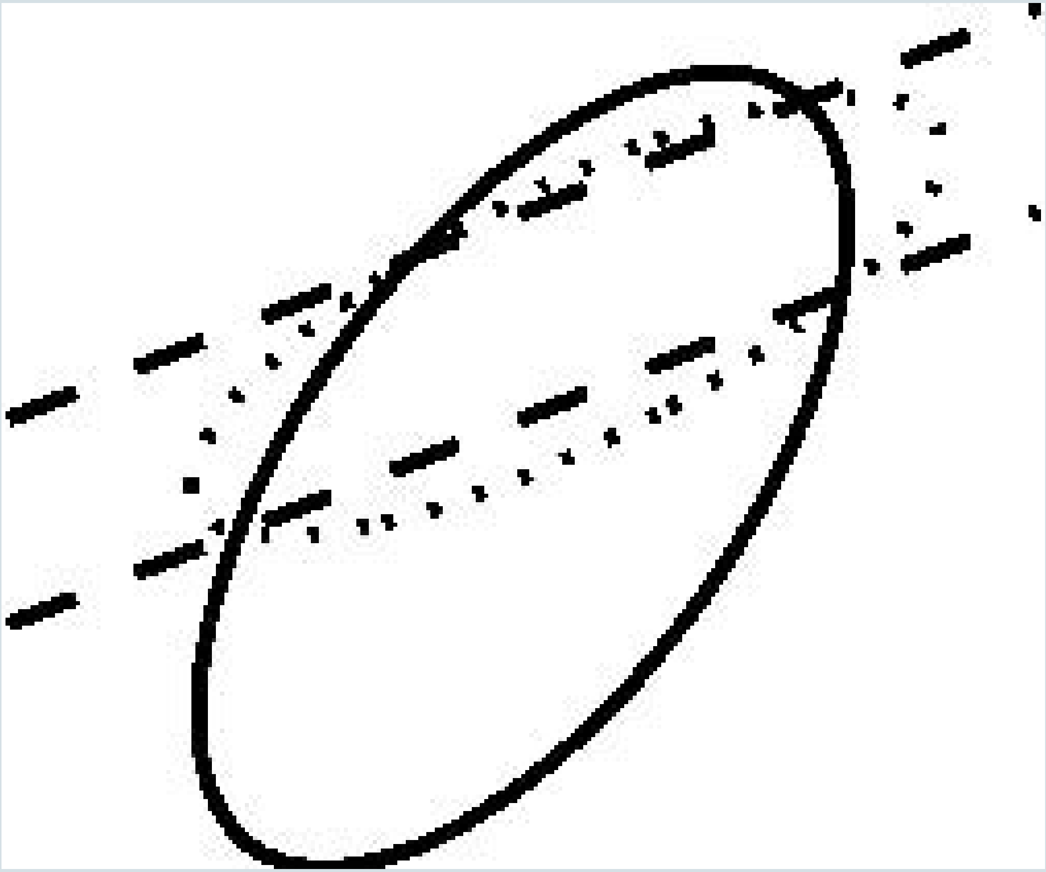
Unfalsified control

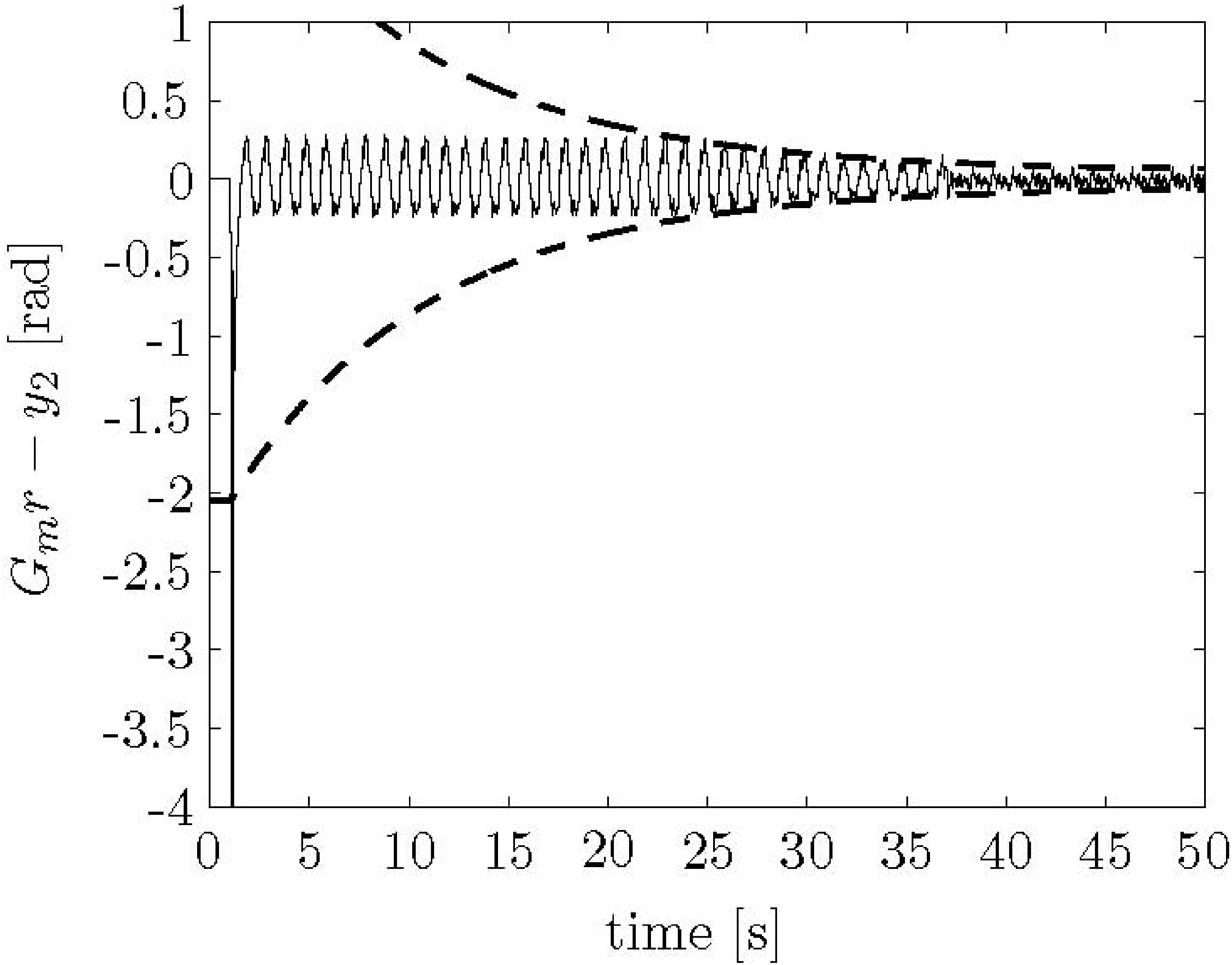
Given a set of controllers, implement one, use the I/O data, and check which part of the set is not feasible, then change the set and iterate

Safanov, Tsao 1997

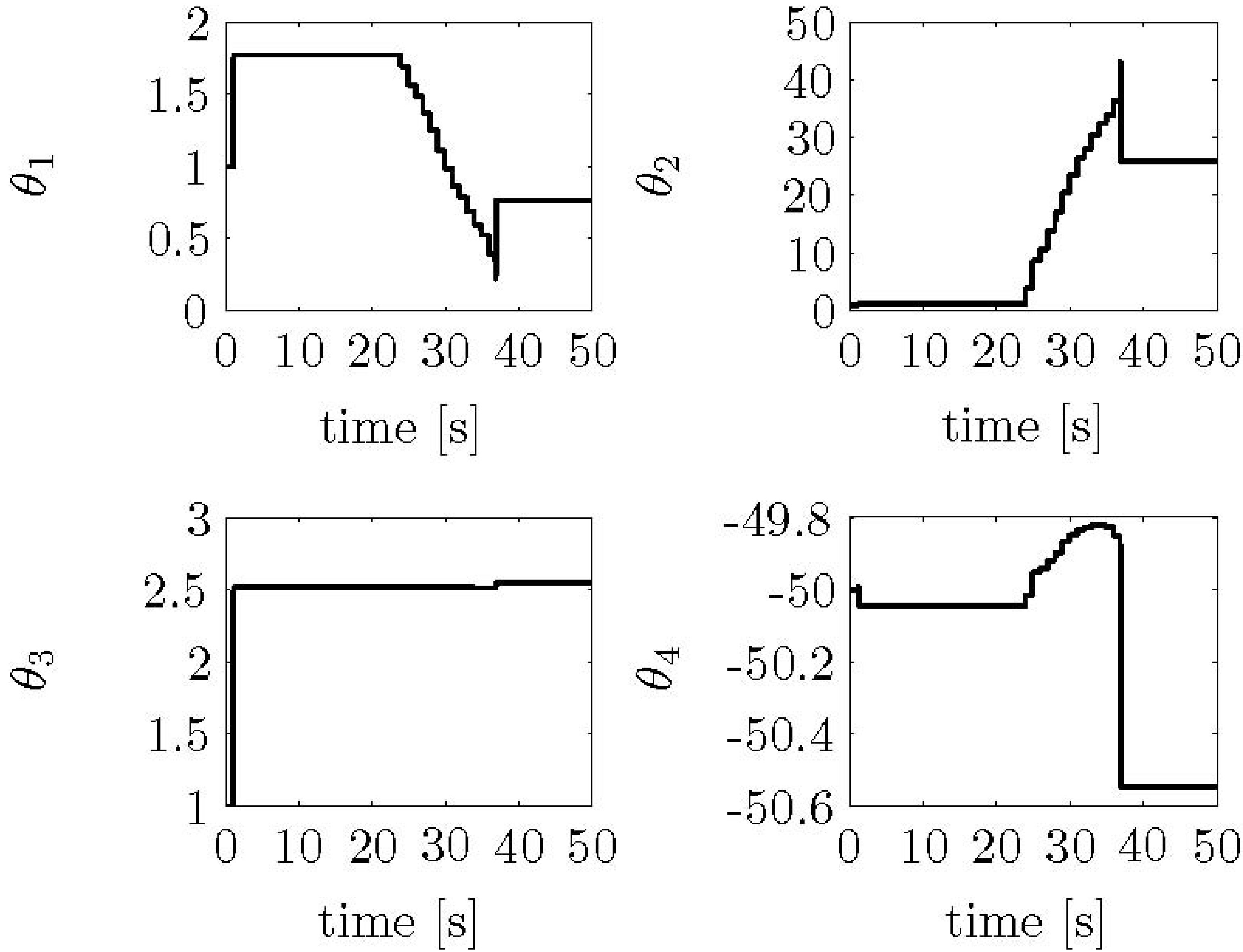

Unfalsification algorithm
Y_m
$G_m(s)$
θ^*
R_v
$w(u,y)$
r
C
u
P
y


Load
Flexible bar
Motor
PARVEX





$G_m r - y_2$ [rad]
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
5
10
15
20
25
30
35
40
45
50
time [s]


θ1
θ2
θ3
θ4
time [s]
time [s]
time [s]
time [s]

Explore Motion Control Properties

- experimentation is ‘cheap’

  Disturbance Design Cycle: 7 min FRF measurement, model, loopshape, implementation *Data based*
- plant decoupling, i.e. SISO *MIMO disturbances*
- feedforward: low-order model-based *Learning control*
- feedback: loopshaping *nonlinear control*
- key limitation: bode gain/phase - sensitivity integral

The End