

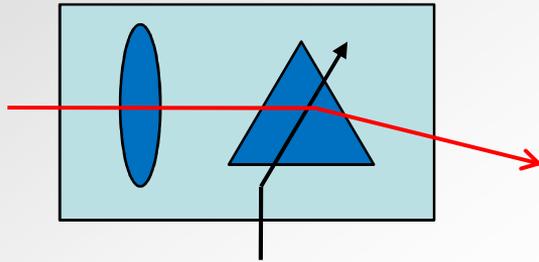
Piezo actuators as orbit correctors

Jürgen Pfingstner

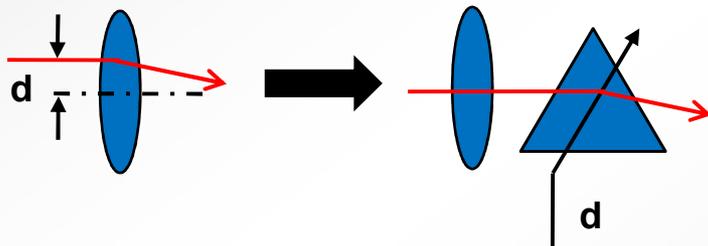
25th of June 2009

Principle and Motivation

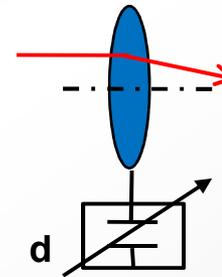
1.) Corrector coil as orbit corrector



2.) Action of a displaced quadrupoles

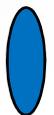


3.) Actuated quadrupoles as orbit corrector



Advantages :

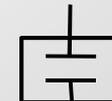
- Simpler magnet design
- Just one system for Beam-based feedback and alignment
- Cost reduction



Quadrupole (magnet)



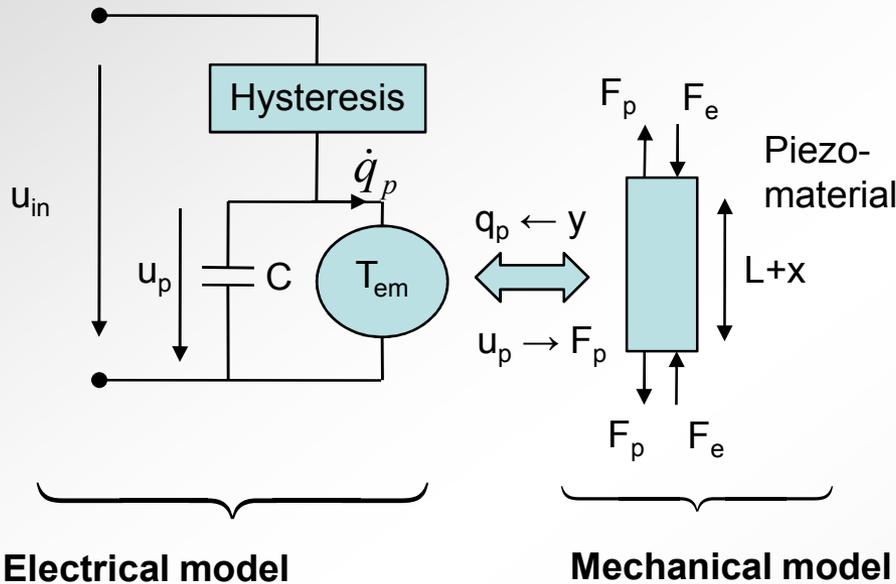
Dipole (magnet)



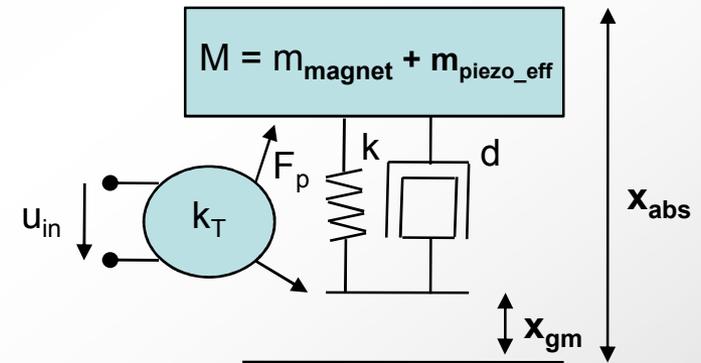
Piezo actuator

Math. model of a piezo actuator

“Complete” electromechanical model of a piezo cristall [1], [2]:



Simple electromechanical model of a piezo cristall [1], [3]:



Electrical model:

- **Hysteresis:** Assumed to be compensated by feedback
- **Capacitor:** Assumed to be loaded fast enough by amplifier

Mechanical model:

- **PDE** is approximated by a **ODE** of second order

Simplified Model

2nd Newton's law:

$$M\dot{x}_{abs} = \sum F = -d(\dot{x}_{abs} - \dot{x}_{gm}) - k(x_{abs} - x_{gm}) + kk_{piezo}u_{in}$$

$$\ddot{x}_{abs} + d\dot{x}_{abs} + kx_{abs} = d\dot{x}_{gm} + kx_{gm} + kk_{piezo}u_{in}$$



Laplace transformation

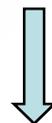
$$x_{abs}(s) = \frac{\frac{d}{M}s + \frac{k}{M}}{s^2 + \frac{d}{M}s + \frac{k}{M}}x_{gm}(s) + \frac{\frac{kk_T}{M}}{s^2 + \frac{d}{M}s + \frac{k}{M}}u_{in}(s)$$

$$= \frac{\delta\omega_0 s + \omega_0^2}{s^2 + 2\delta\omega_0 s + \omega_0^2}x_{gm}(s) + \frac{\omega_0^2 k_T}{s^2 + 2\delta\omega_0 s + \omega_0^2}u_{in}(s)$$

ω_0 ... resonance frequency

δ ... damping factor

k_T ... voltage to length conversion



State space representation

$$\begin{bmatrix} x_{abs} \\ \dot{x}_{abs} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_0^2 & -2\delta\omega_0 \end{bmatrix} \begin{bmatrix} x_{abs} \\ \dot{x}_{abs} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & \omega_0^2 k_T \end{bmatrix} \begin{bmatrix} 2\delta\omega_0 \dot{x}_{gm} + \omega_0^2 x_{gm} \\ u_{in} \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\omega_0^2 & -2\delta\omega_0 \end{bmatrix} \begin{bmatrix} x_{abs} \\ \dot{x}_{abs} \end{bmatrix} + \begin{bmatrix} x_{gm} \\ 2\delta\omega_0 \dot{x}_{gm} + \omega_0^2 x_{gm} + \omega_0^2 k_T u_{in} \end{bmatrix}$$

2 measurements:

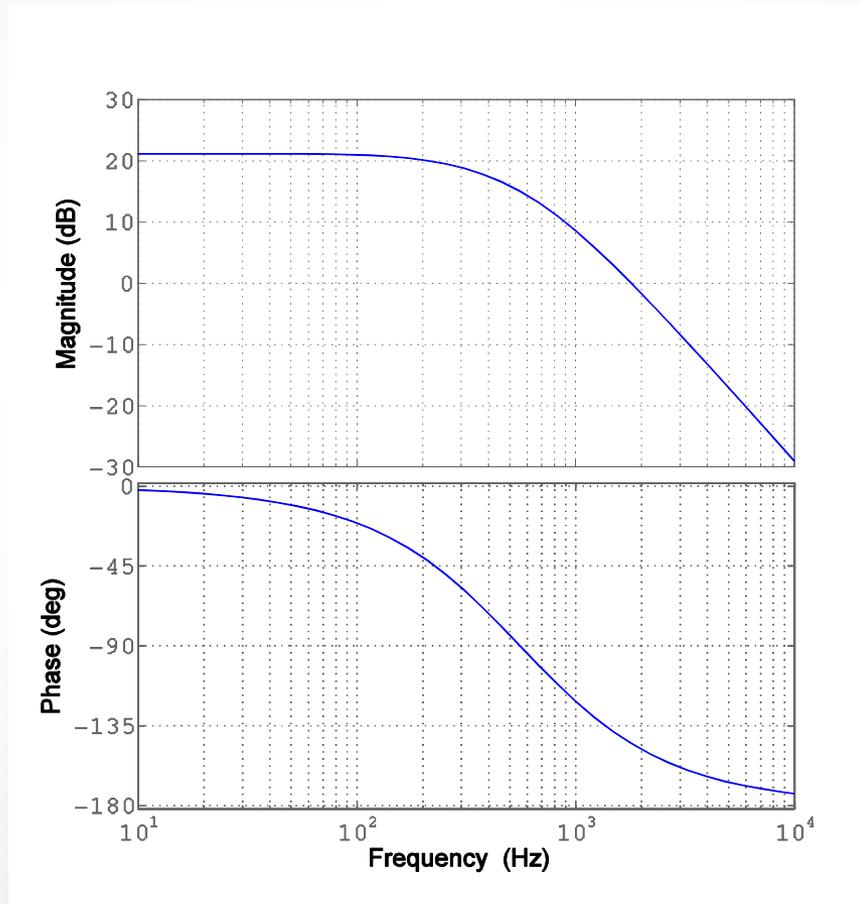
y1 ... Length of the piezo ($x_{abs} - x_{gm}$)

y2 ... vertical acceleration of the magnet (\ddot{x}_{abs})

Piezo amplifier model

- In laboratory an amplifier (E-503) from company PI (Physik Instrumente) available
- Estimation of the transfer function due to curve in data sheet
- Assumption: second order linear system
- DC gain of app. 10

$$Amp(s) = k_{amp} \frac{1}{T1_{amp} T2_{amp}} \frac{1}{s^2 + \left(\frac{1}{T1_{amp}} + \frac{1}{T2_{amp}} \right) s + \frac{1}{T1_{amp} T2_{amp}}}$$



Ground motion and noise model

Based on the ground motion models of A. Sery and O. Napoly [4]:

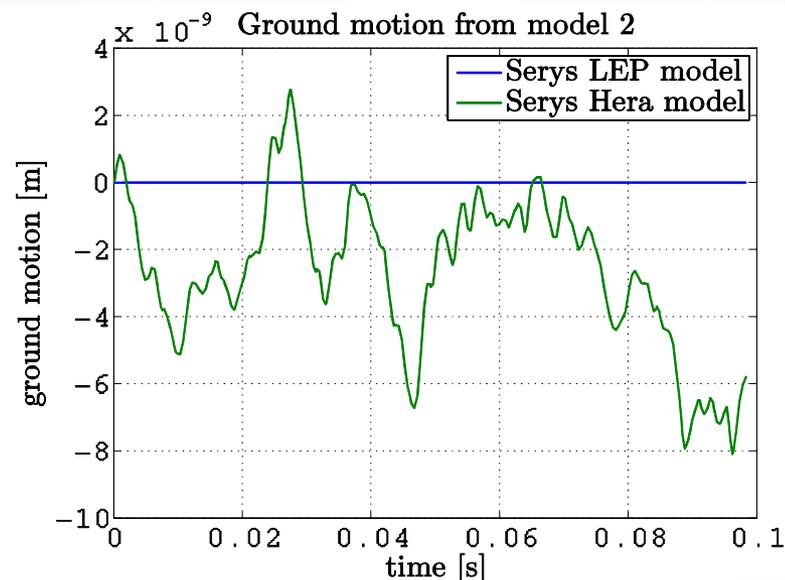
- Original model not in form that can easily be implemented in Matlab (not a rational tf):

$$p(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left(\frac{A}{\omega^2 k^2} [1 - \cos(L_0 k)] + D(\omega) U(\omega, k) \right) dk$$

- Approximating his model with a few simple transfer functions: 2 low passes of first order, 2 peaks with help of second order function and 2 lead elements.

Two different ground motion models were implemented by noise shaping filters:

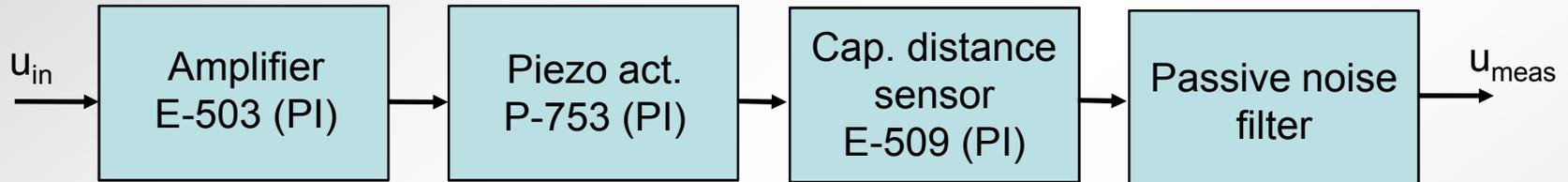
- LEP model: in quiet conditions (at night and with accelerator turned off)
- Hera model: with big cultural noise component (accelerator on)



Noise of the sensors:

- Capacitive distance sensor:
 - With measurements in lab: +/- 3nm rms with main component at 200kHz
 - proper noise filter designed (help of M. Gasior), cutoff at 16 kHz
- Accelerometer:
 - Assumed to be about +/- 1nm rms

Parameter identification



Amplifier:

- $k_{amp} = 11.45$
- $T1_{amp} = 0.23$ ms
- $T2_{amp} = 0.35$ ms

Piezo actuator:

- $k_T = 0.67$
- $\delta = 0.13$
- $\omega_0 = 2\pi$ 1538 Hz

Cap. Distance sensor:

- big noise signal
- main component around 200kHz
- $80\text{mV} \cong 80\text{nm}$

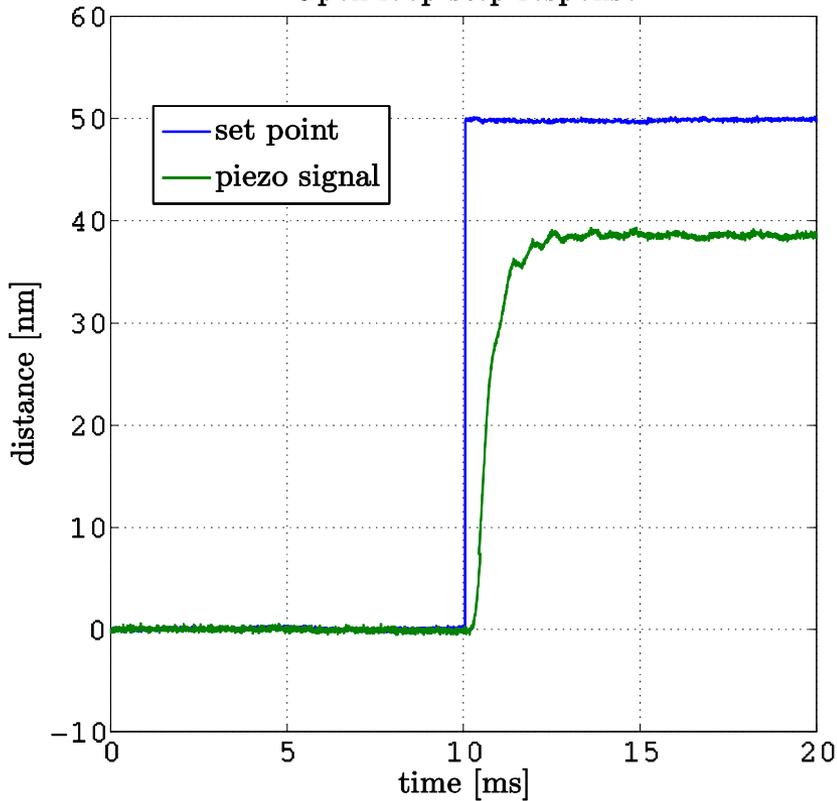
Design and building of a noise filter:

- with help from M. Gasior (BE-BI)
- second order
- passiv
- cutoff at app. 16kHz
- DC gain 0.929



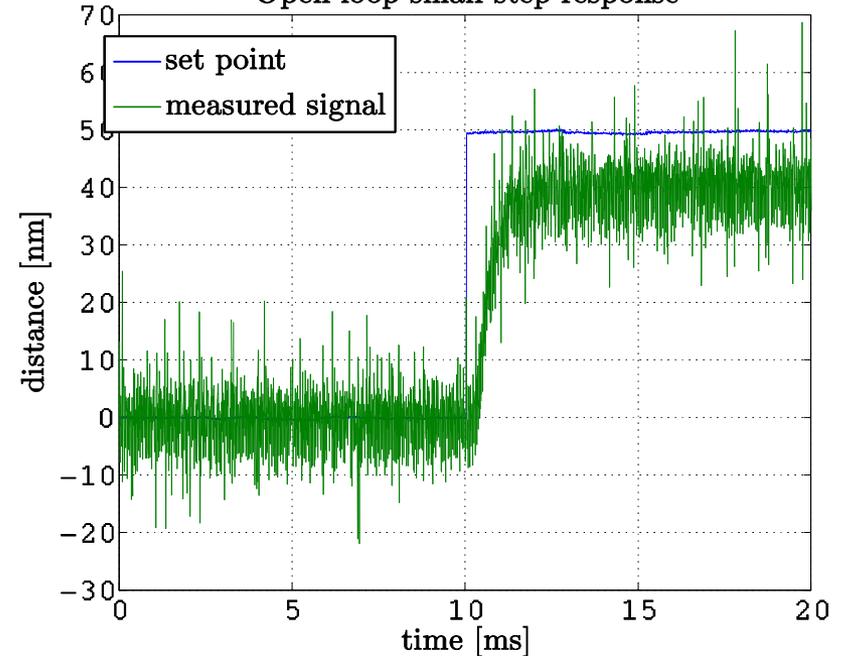
System behavior and model verification

Open loop step response



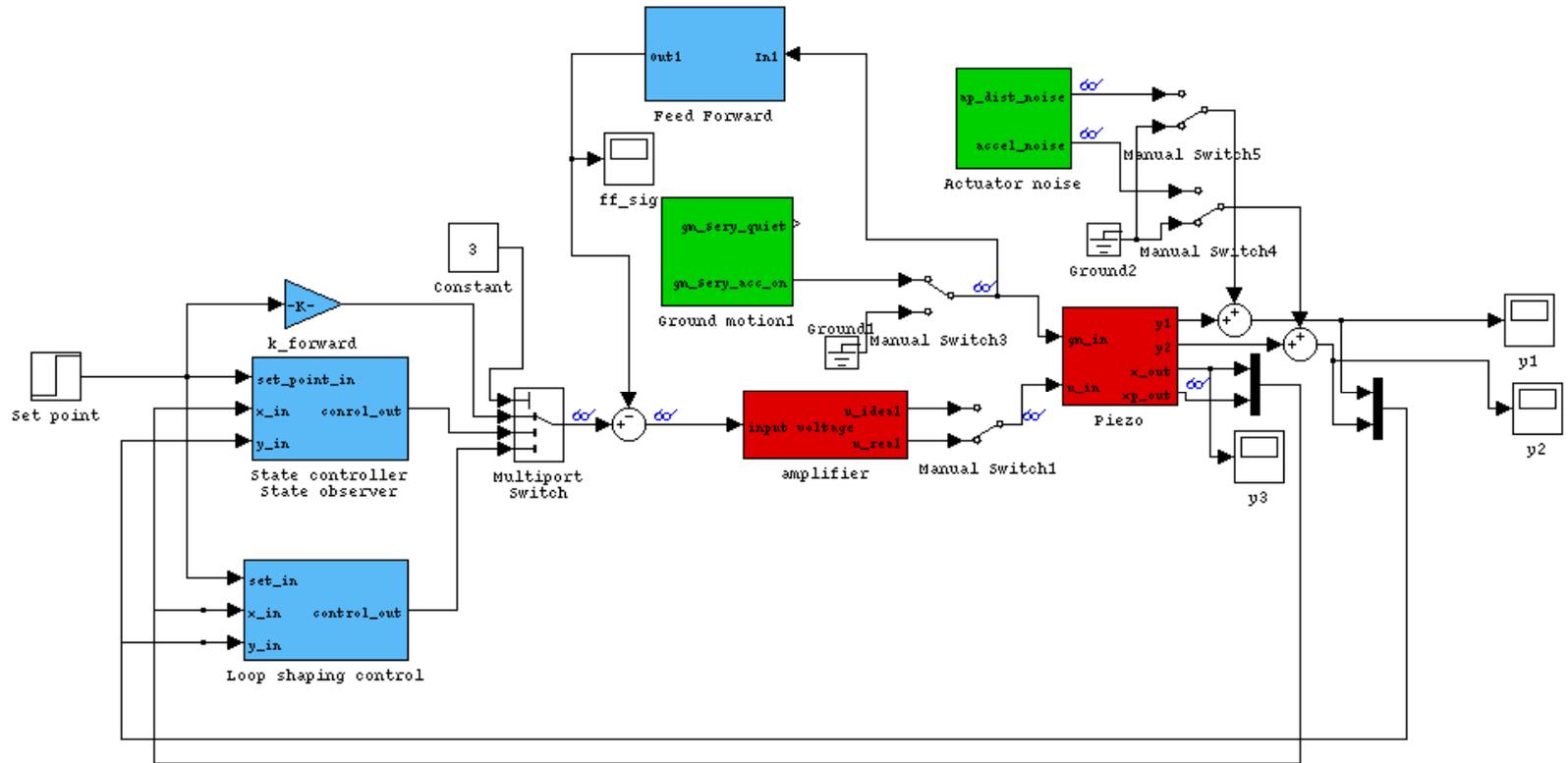
Simulation delivers the 'same' curves
-> Reality and model fit very well

Open loop small step response



Remaining meas. noise level :
app. 3nm rms

Simulation in Matlab/Simulink



Solver:

- variable step size solver
- ode45 (Dormain-Prince)

PI controller design

- The two poles of the amplifier are dominating. Piezo behavior is damped down
- Design by shaping of the open loop:

$$L(s) = C(s)G(s)$$

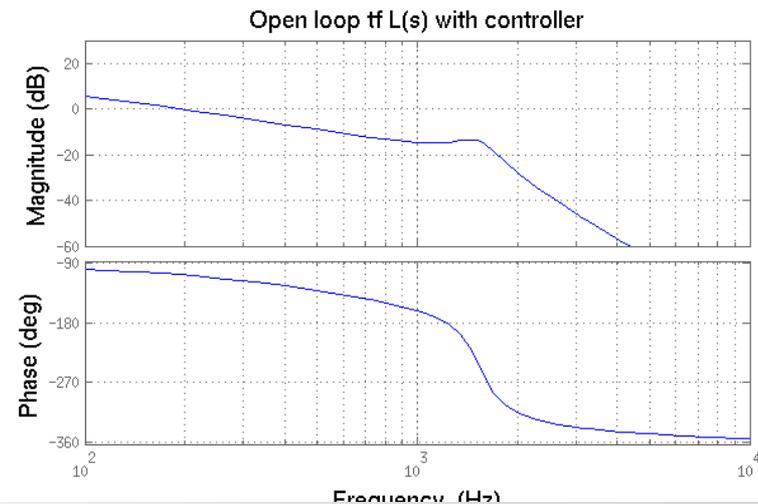
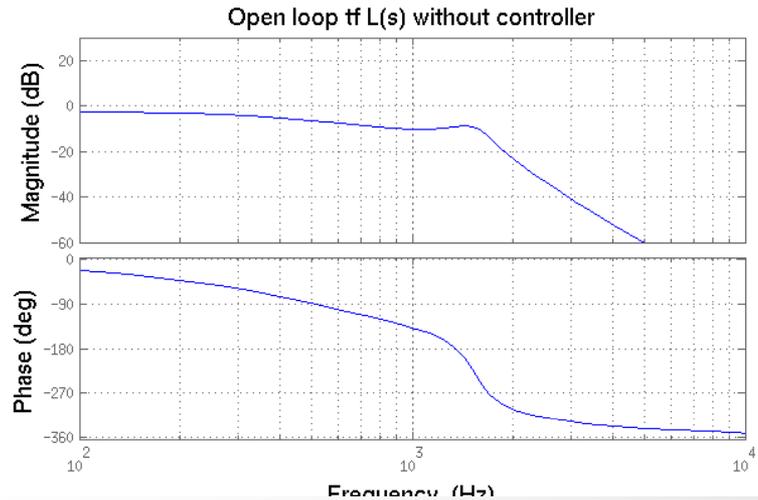
- Wanted form:

$$L(s) \approx \frac{k}{s} \frac{1}{(s + \omega_c)^2}$$

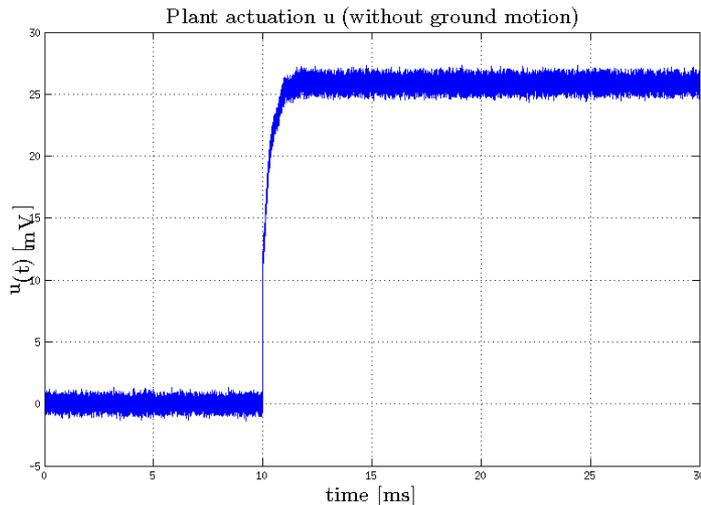
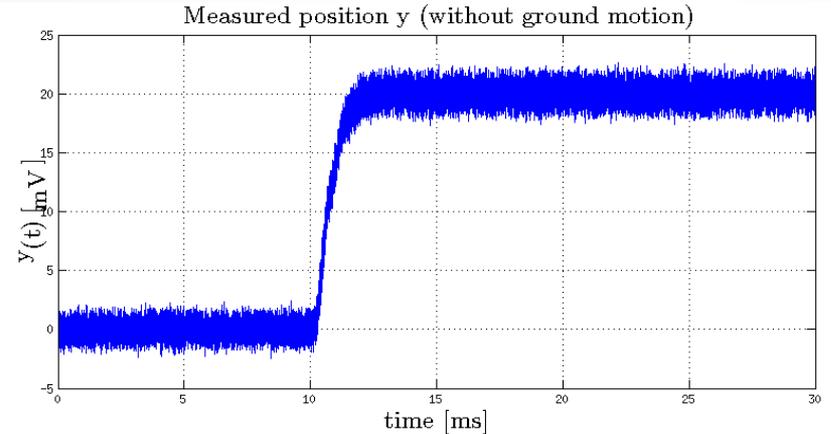
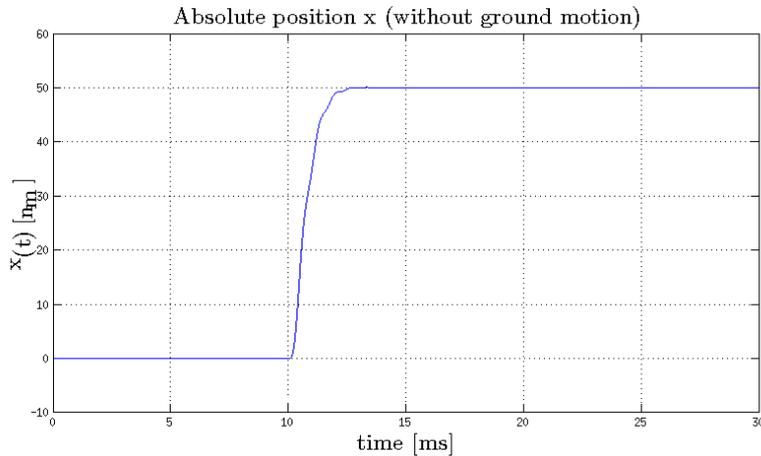
- Shaping with PI controller

$$C(s) = k_p + \frac{k_i}{s} = k_p \frac{s + \frac{k_i}{k_p}}{s}$$

- Strategy:
 - Piezo and amplifier is fast enough
 - Add integrator
 - Cancel first pole of the amplifier with the zero
 - Damp down the system with the factor k_p



PI controller results



- The PI controller meets the desired specifications of achieving the wanted value within 10 ms.
- Measured value y (piezo length) and controlled value x (absolute position) are not the same! White noise on y measurement does not influence control of x .
- The actuating signal u does have any overshoot

Scaling piezo behavior for heavy magnet

1.) Resonance frequency of a piezo actuator

The eigenfrequency can be calculated [3] as:

$$\omega_0 = \frac{1}{2\pi} \sqrt{\frac{k_t}{m_{eff} + m_{load}}}$$

$$k_t = 200 \cdot 10^6 \frac{N}{m} \quad \dots \text{Spring constant of the piezo P-225.40 (high load)}$$

$$m_{eff} \approx \frac{m_{piezo}}{3} = 0.1kg \quad \dots \text{Effective mass of the piezo}$$

$$m_{load} = \frac{m_{magnet}}{3} = 110kg \quad \dots \text{Biggest CLIC QP (1.9m) on 3 actuators}$$

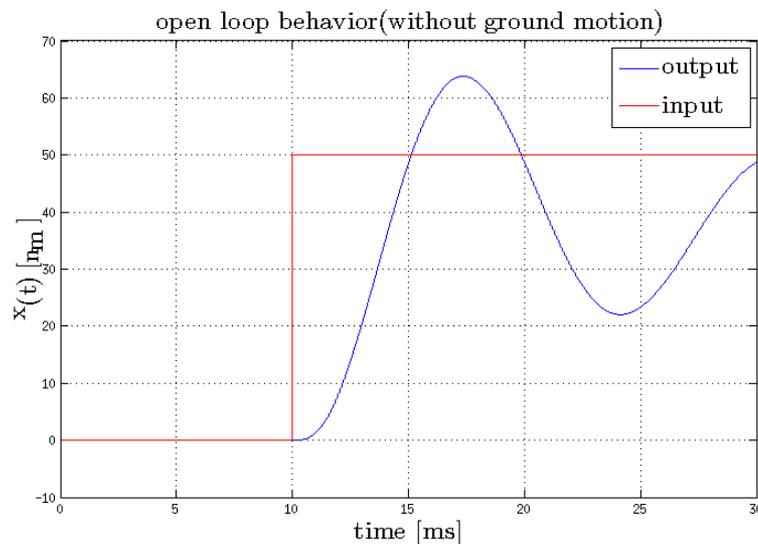
$$\rightarrow \omega_0 = 74.34Hz$$

2.) Damping factor of a piezo actuator

- According to PI for all actuators between 0.2 and 0.1
- Assumed to be the same as for the laboratory model P-753: $\delta = 0.13$

3.) Piezo amplifier

- According to PI similar than the one in the laboratory
- Could probably be improved by R&D effort ('just' cost)
- Assumed to be the same as in laboratory: E-503



Design of the high load piezo controller

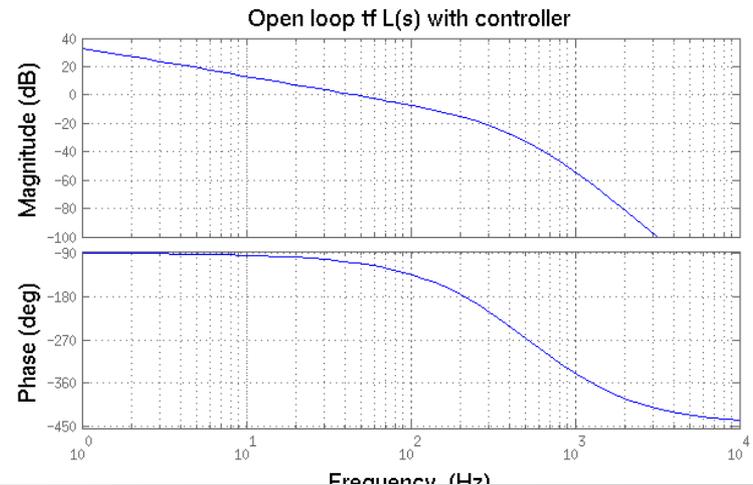
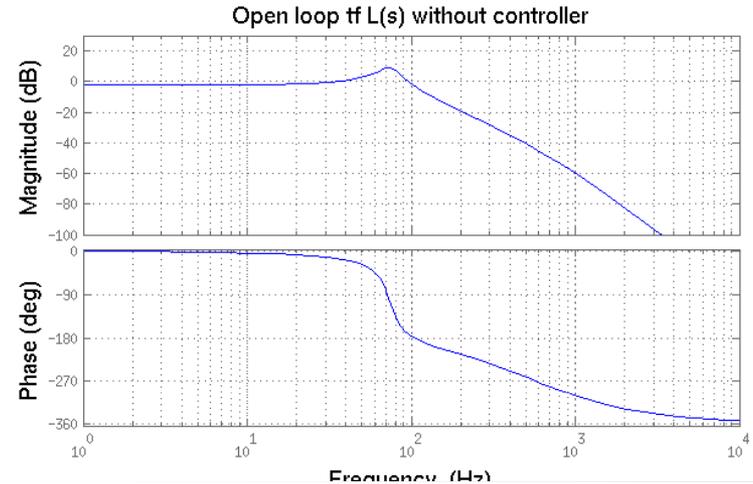
- Now the piezo behavior is dominating (conjugate complex pole)
- A simple PI controller can not correct for that since the w_0 is too low to damp down.

- Strategy:

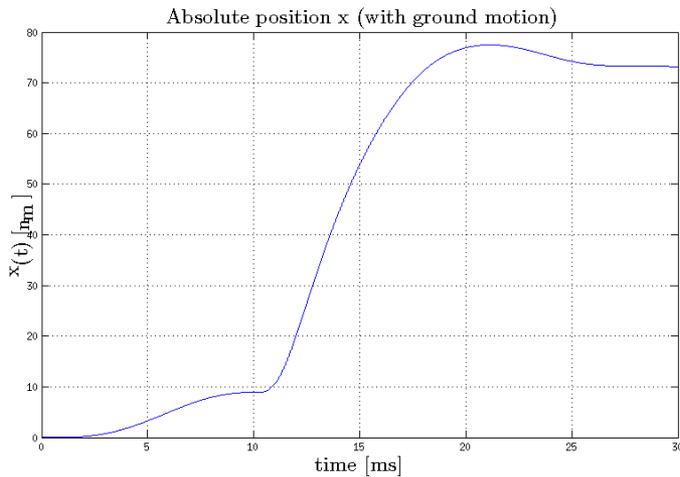
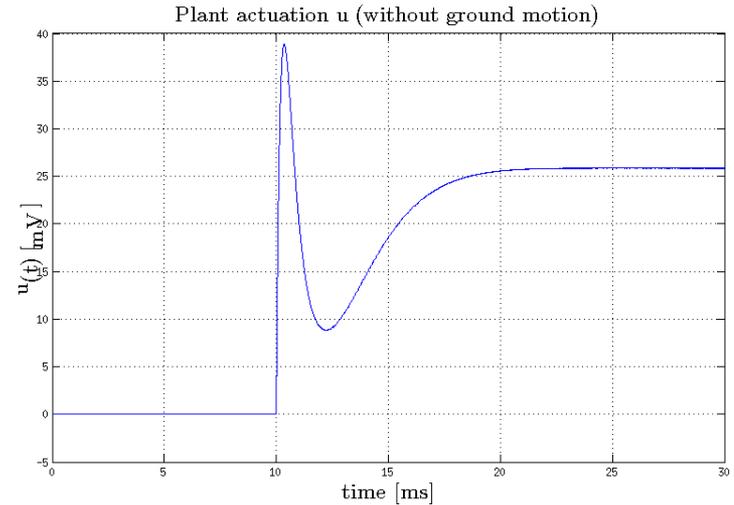
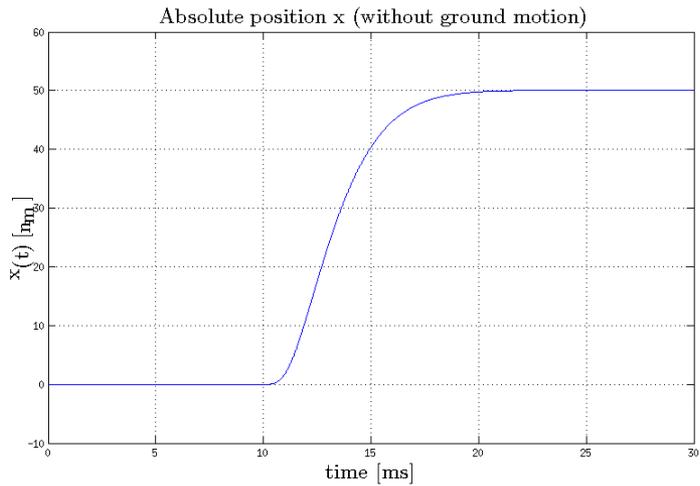
- Cancel conjugate complex poles with a conjugate complex zeros $C(s) = \frac{k}{s}$
- Add integrating behavior
- Add two roll off poles to make the controller strictly proper
- Adjust k_p to get the wanted dynamical behavior

- Resulting Controller:

$$C(s) = \frac{k_p}{s} \frac{s^2 + 2\delta\omega_0 + \omega_0^2}{(s + \omega_{cut})^2}$$



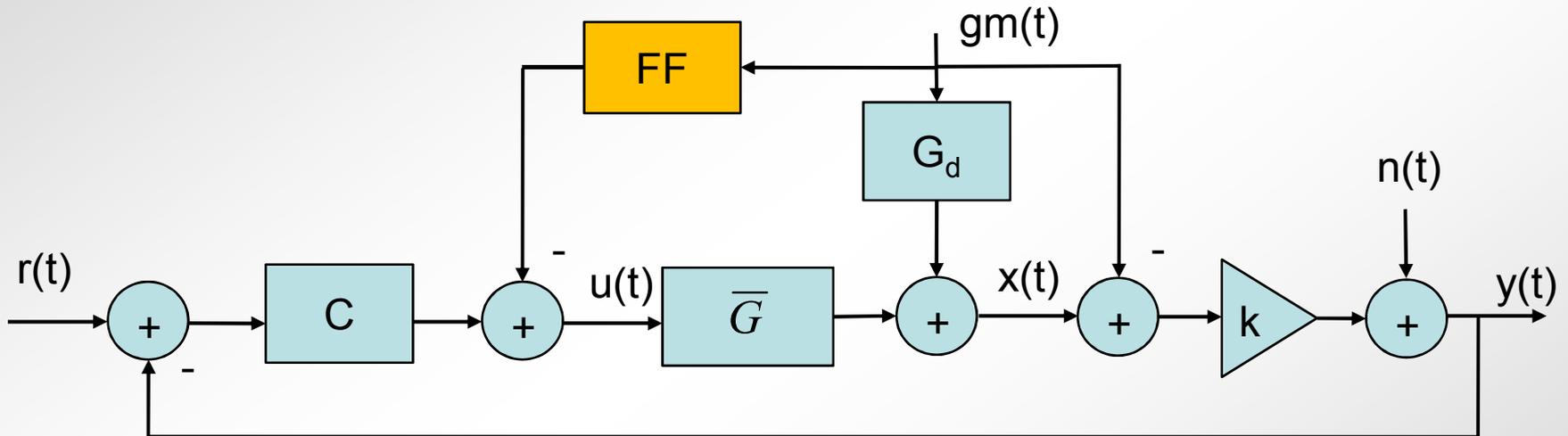
Performance of the high load controller



- Loop shaping controller meets the specifications without any margin.
- The actuating signal has a big overshoot at the amplifier input but not at the piezo input. A piezo amplifier with wider input range could be interesting
- With ground motion the design is not sufficient

Feed forward design

- More detailed look on the influence of ground motion:



- Transfer function from ground motion to $x(t)$ with feedforward:

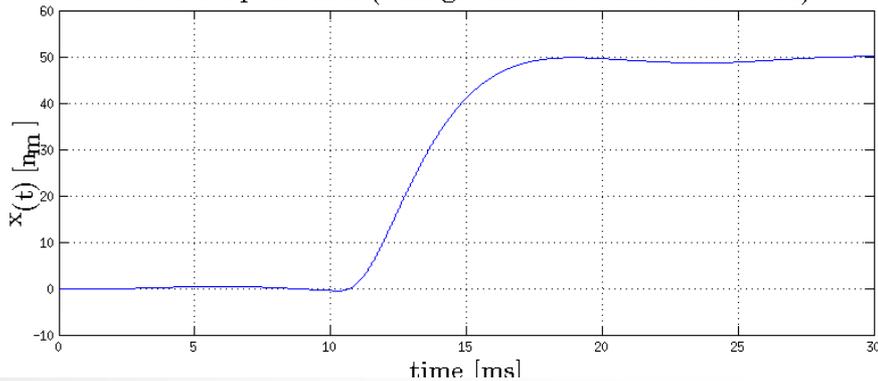
$$x(s) = \frac{1}{1 + k\bar{G}C} (G_d + k\bar{G}C - \bar{G}FF) gm(s) = 0 \cdot gm(s)$$

$$\rightarrow FF = \bar{G}^{-1}G_d + kC$$

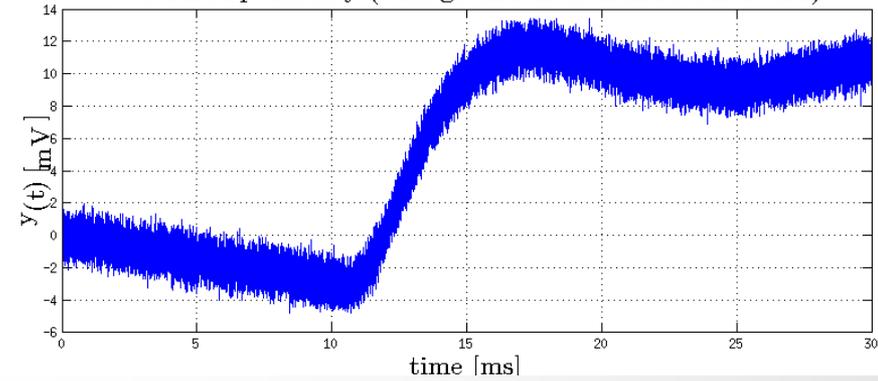
- Roll off poles have to be added to make FF proper.

Performance of the final strategy

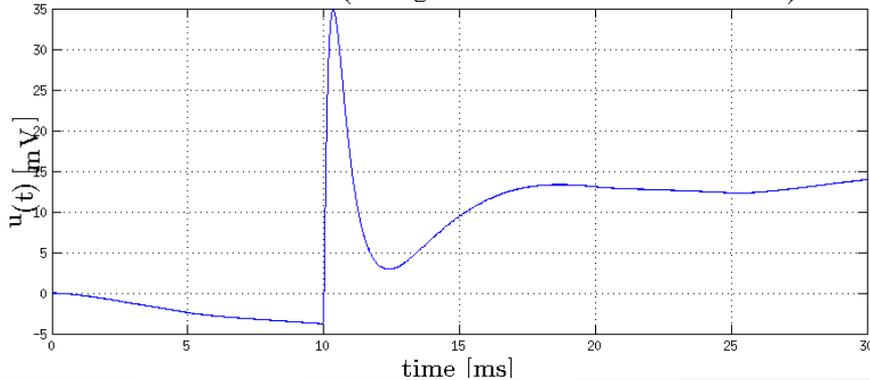
Absolute position x (with ground motion and feedforward)



Measured position y (with ground motion and feedforward)



Plant actuation u (with ground motion and feedforward)



- With feed forward strategy, the specifications can be met, if the sensor signal represents the ground motion well enough.
- Interestingly enough the measured signal y the controller acts on has completely different form than the controlled variable x .

Design alternatives investigated

1.) State controller with Lueneberger observer:

- Results in lower actuating signal u at same plant speed
- Implementation of feed forward more difficult and not investigated yet (no time)
- **No integrating behavior**
- PI State controller would be **alternative, but feed forward not directly implementable** [6]

2.) Two degree of freedom controller instead of single feedback and feedforward

- Classical approach decouples disturbance rejection and set point following.
- The usual design of the feedback for disturbance rejection [5] results in an **unstable loop**. The reason for that is the unusual action of the disturbance (ground motion) on the measured signal y

Conclusions

- **The use of a piezo actuated quadrupole as an orbit corrector is possible** with the following **assumptions** made:
 - The scaling of the small to the big is valid (it is according to piezo company PI).
 - The **ground motion can be accurately measured** not only as an acceleration but a displacement in real time (biggest assumption).
 - The piezo amplifier should maybe have a bigger input output range to be able to act on fast control action resulting in big actuating signals. But optimization can still be done.
- A first design is made which should be further tested and improved (maybe state controller approach is better).
- The following **influences** have **not** been **included** in the simulation yet:
 - **Other disturbances** than ground motion, that act on the quadrupole directly (sound, electromagnetic fields, cooling water)
 - **Support structure** (since no reliable model is available yet)

References

- [1] H. Adriaens, W.L. de Koning, and R. Banning. Modeling piezoelectric actuators. IEEE/ASME transactions on mechatronics, 5(4):331–341, 2000.
- [2] M. Goldfarb and N. Celanovic. Modeling piezoelectric stack actuators for control of micromanipulation. IEEE Control Systems Magazine, 17(3):69–79, 1997
- [3] PI (Physik Instrumente), [http://www.physikinstrumente.com/en/pdf extra/PI designing with piezo actuators tutorial 2005c.pdf](http://www.physikinstrumente.com/en/pdf_extra/PI_designing_with_piezo_actuators_tutorial_2005c.pdf). Designing with Piezoelectric Transducers: Nanopositioning Fundamentals, 2005
- [4] Andrey Sery and Olivier Napoly. Influence of ground motion on the time evolution of beams in linear colliders. Phys. Rev. E, 53:5323, 1996
- [5] Sigurd Skogestad and Ian Postlethwaite. Multivariable Feedback Control: Analysis and Design. Wiley-Interscience, 2005. ISBN: 0-470-01168-8
- [6] Otto Föllinger. Regelungstechnik: Einführung in die Methoden und ihre Anwendung. Hüthig Buch Verlag Heidelberg, 1994. ISBN: 3-7785-2915-3

Thank you for your attention!

Sensor signal reconstruction

Fuer naechstes CLIC STA meeting einen zweiten Teil hier (7 Folien (1 Tag Arbeit)):

- Grundproblem
- Idee zur Signalrueckgewinnung
- Ergebnisse eines normalen inversen Filters
- Konzept des Blind observers
- Ergebnisse
- Probleme des Blind Observers
- Resume