Verification of the Design of the Beam-based Controller

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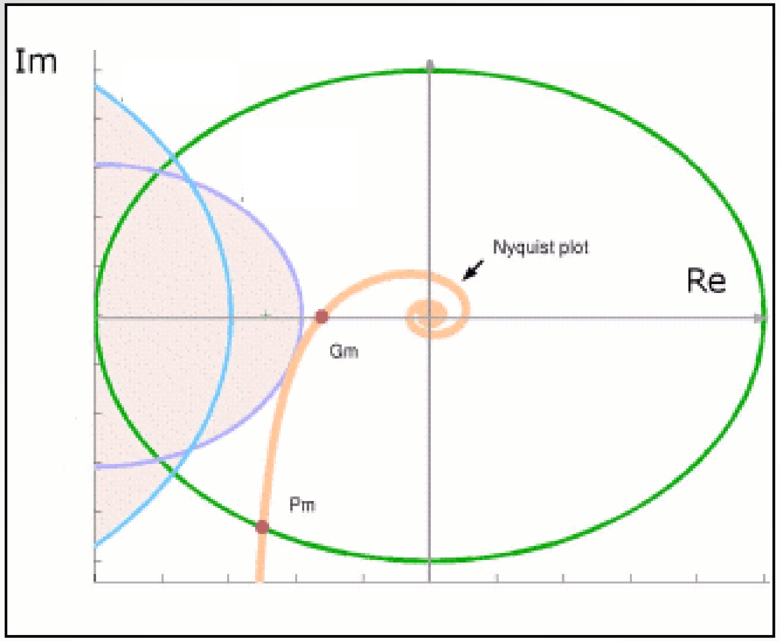
Content



1. Analysis of the contoller with standard control engineering techniques

2. Uncertanty studies of the response matix and the according control performance

Analysis of the contoller with standard control engineering techniques

- Daniel developed a controller, with common sense and feeling for the system

- I tried to verify this intuitive design with, more abstract and standardized methods:
  - Standard nomenclature
  - z – transformation
  - Time-discrete transfer functions
  - Pole-zero plots

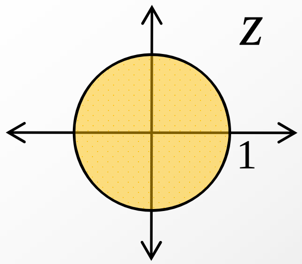
z – Transformation

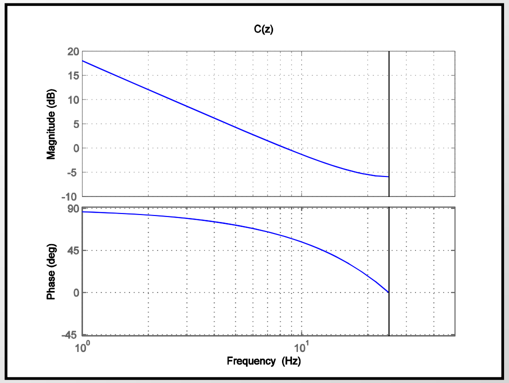
- Method to solve recursive equations
- Equivalent to the Laplace – transformation for time-discrete, linear systems
- Allows frequency domain analysis

$$G(z) = \sum_{i=0}^{\infty} g[i] z^i \qquad z = e^{i\omega T_d}$$

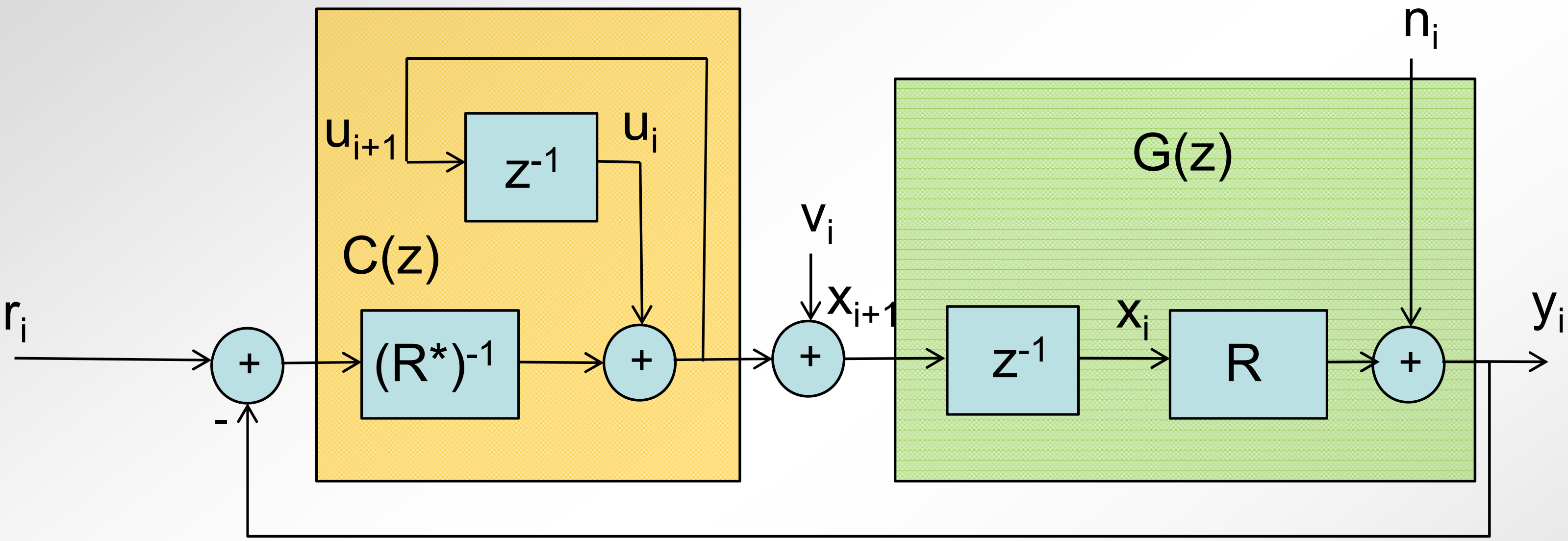
→ $g[i]$ → → z – transfer function G(z) → Discrete Bode plot

Discrete System





Model of the controlled system



r_i … set value (0)
y_i, … BPM measurements
v_i … ground motion
n_i … BPM noise

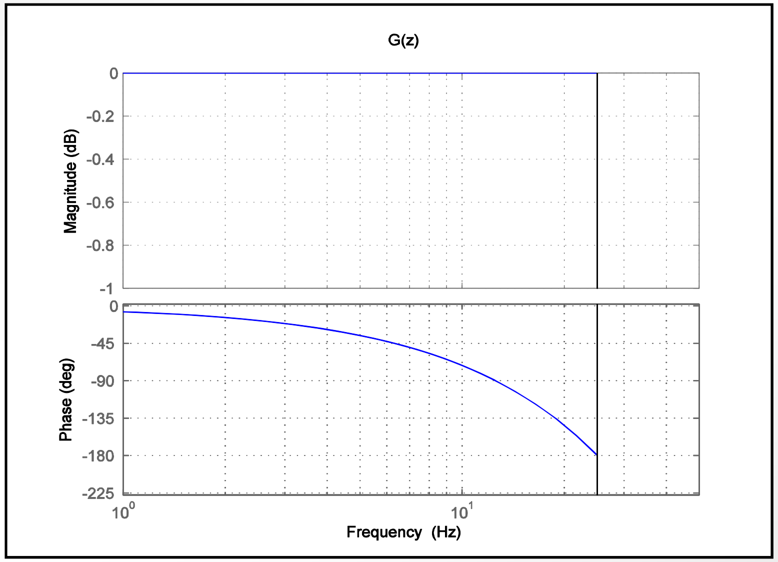
u_i, u_{i+1} … controller state variables
x_i, x_{i+1} … plant state variables (QP position)

C(z) … Controller
G(z) … Plant

System elements

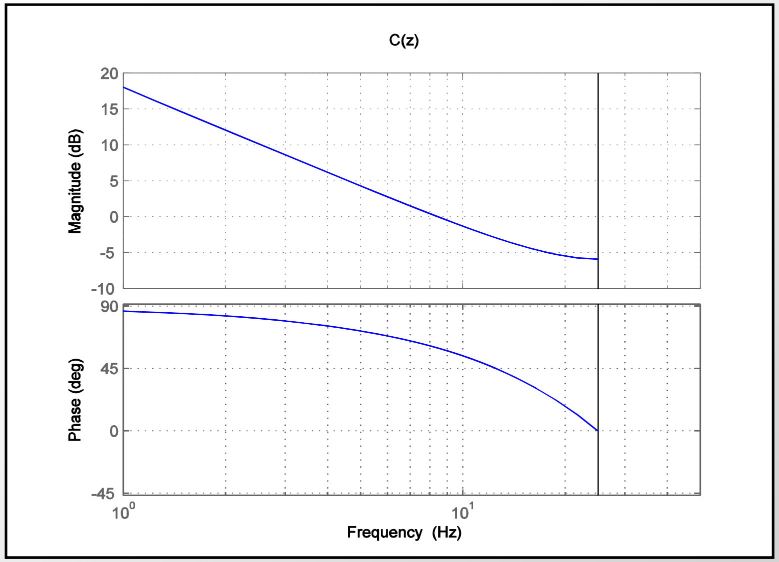
$$G(z) = \frac{R}{z}$$

- simple
- allpass
- non minimum phase



$$C(z) = (R^*)^{-1} \frac{z}{z-1}$$

- I controller

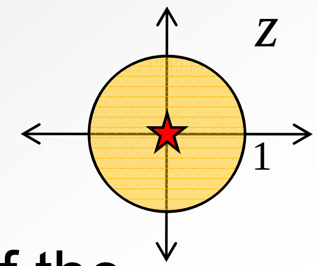


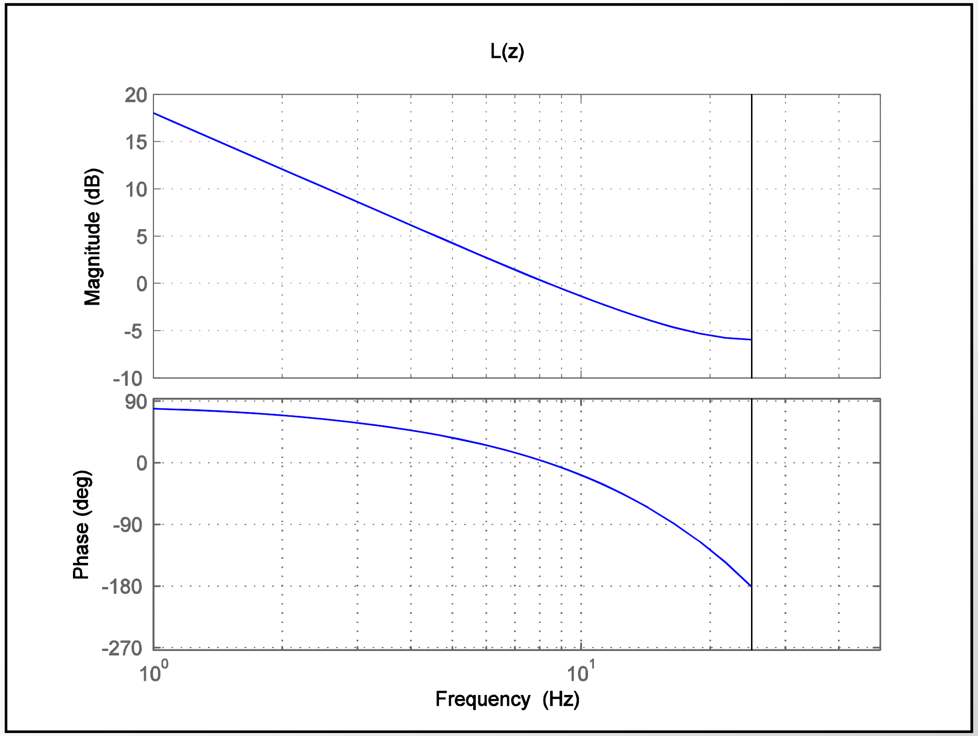
Be aware about the not mathematical correct writing of the TF (matrix instead of scalar)

Stability and Performance

$$L(z) := C(z)G(z) = R(R^{*})^{-1}\frac{1}{z-1}$$

- Stability
  - necessary attenuation at high frequencies
  - all poles at zero





- Performance of the interesting transfer functions
  - $V(z) := \frac{y(z)}{v(z)} = \frac{G(z)}{1+L(z)} = R\frac{z-1}{z}\frac{1}{z-(1-R(R^{*})^{-1})}$
  - $N(z) := \frac{n(z)}{v(z)} = \frac{1}{1+L(z)} = \frac{z-1}{z-(1-R(R^{*})^{-1})}$
  - $R(z) := \frac{r(z)}{v(z)} = \frac{L(z)}{1+L(z)} = R(R^{*})^{-1}\frac{1}{z-(1-R(R^{*})^{-1})}$

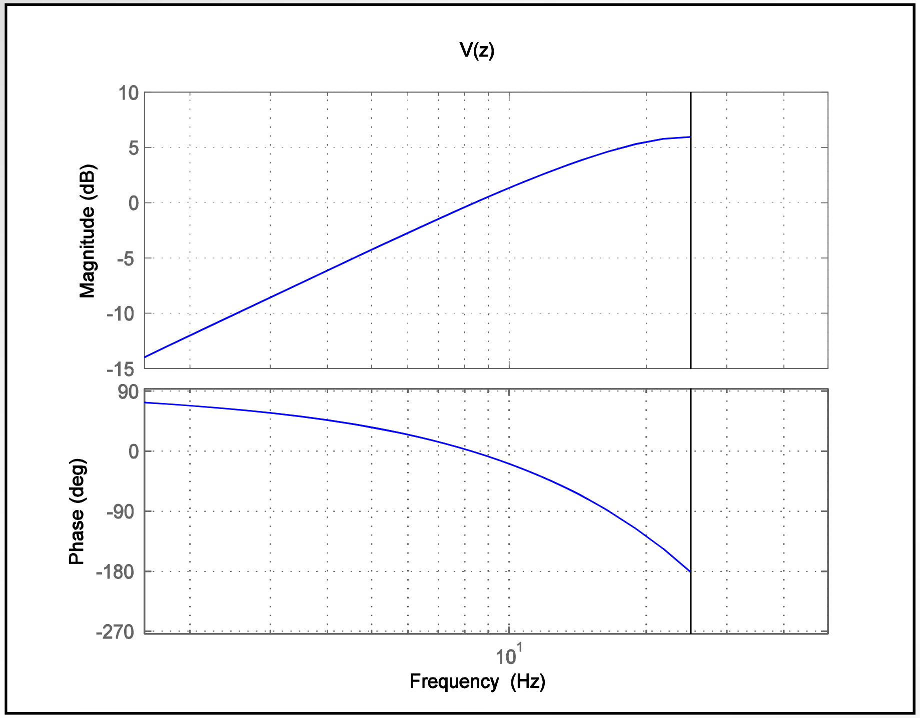
Important transfer functions

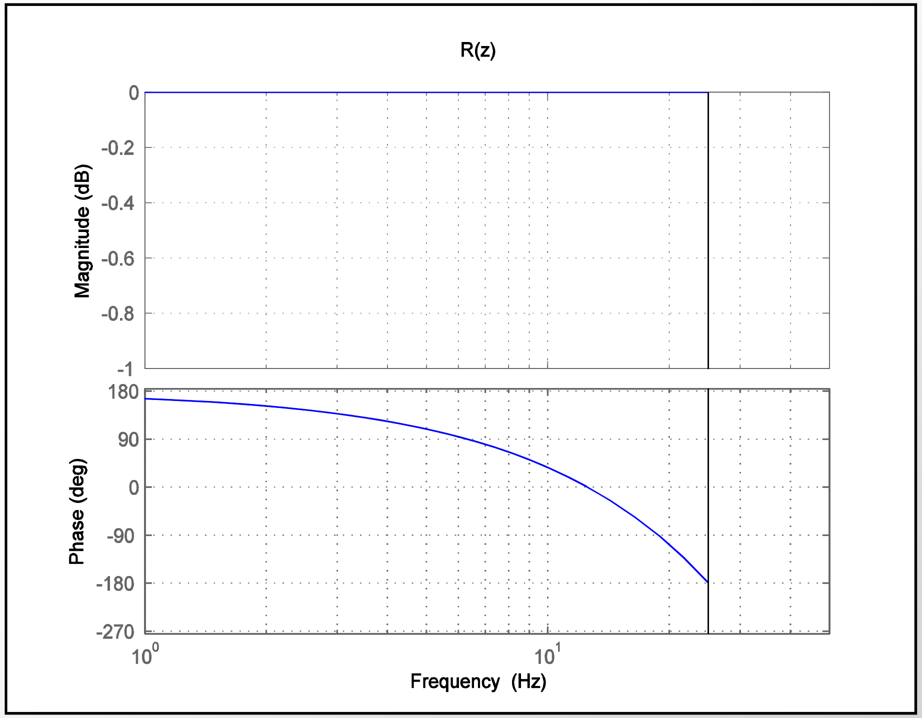
$$V(z) \approx N(z)$$

(error behaviour)

$$R(z)$$

(set point following)





Conclusions

- Controller is:
  - very stable and robust (all poles at zero)
  - integrating behavior (errors will die out)
  - good general performance
  - simple (in most cases a good sign for robustness)

- Seams to be a very good design in general
  - However: Ground motion has still to be simulated
  - Sensitivity to certain frequencies, could make different trimmed transfer functions necessary or even to an other controller structure (SVD)

Further work

- Simulations with ground motion
- H_∞ optimal controller design, to double check

Uncertanty studies of the response matix and the according control performance

Controller is robust, but is it robust enough?

yes

no

done

- Answer to that question by simulations in PLACET

- Plan A:
  - Use methods from **robust control** to adjust the controller to the properties of the uncertainties (e.g. pole shift)
- Plan B:
  - Use **adaptive control** techniques to estimate R first and than control accordingly

Tests in PLACET

- Test series 1 (Robustness according to machine drift):
  - Use the controller with R^* for the nominal machine
  - Disturb the beam line and the beam in PLACET
- Script in PLACET where the following disturbances can be switched on and off:
  - Initial energy E_{init}
  - Energy spread ΔE
  - QP gradient jitter
  - Acceleration gradient and phase jitter
  - BPM noise
  - Corrector errors
  - Ground motion
- Additional PLACET function *PhaseAdvance*
- Analysis of the controller performance and the resulting R

Results

Quantity	Acceptable values	Nominal values
E_{init}	8.5 – 9.5 GeV	9.0 GeV (≈± 1 %)
σ_E	0.0 – 10.0 %	2.0 % (± <1%)
QP gradient error *3	-0.3 – 0.4 %	≈ 0.1%
Acceleration gradient variation *4	0.0 – 0.3 %	0.0 – 0.3 %
BPM noise *5	0.0 – 1.0 µm (std)	? µm (std)
Corrector errors *5	0.0 – 0.04 µm (std)	? µm (std)

*1 … Always one parameter is changed independently
*2 … Values are according to the single punch emittance
*3 … All QPs are changed in the same manner
*4 … All QPs are disturbed not just the one that is intended to move by 1 µm
*5 …BPM and corrector errors are not yet representative!

Measures for the performance

- Goal: Find properties of R_{dist} that correspond with the controller performance

$$abs_{norm}$$

$$M = R_{dist} - R_{nom}$$

$$m_{norm} = \sum_i \sum_j |m_{ij}|$$

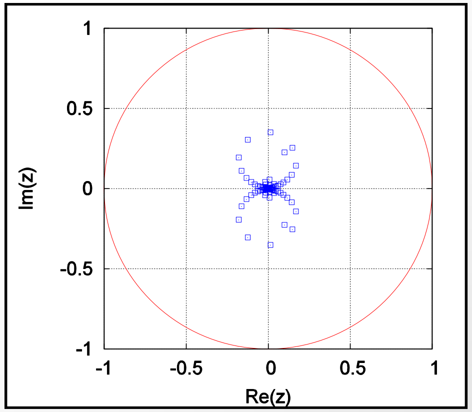
R_{dist} … disturbed matrix
R_{nom} … nominal matrix
abs_{norm} … absolut matrix norm

$$ev_{norm}$$

$$L = R(R^*)^{-1}$$

$$EV = eig(L)$$

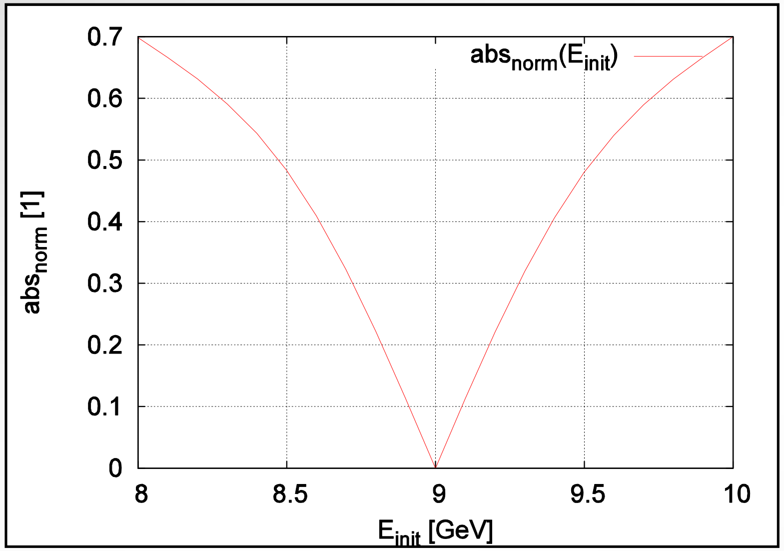
$$ev_{norm} = 1 - \max_i(|ev_i|)$$



ev_{norm} … eigenvalue norm
L … matrix that determines the poles of the control loop

Information from abs_{norm} and ev_{norm}

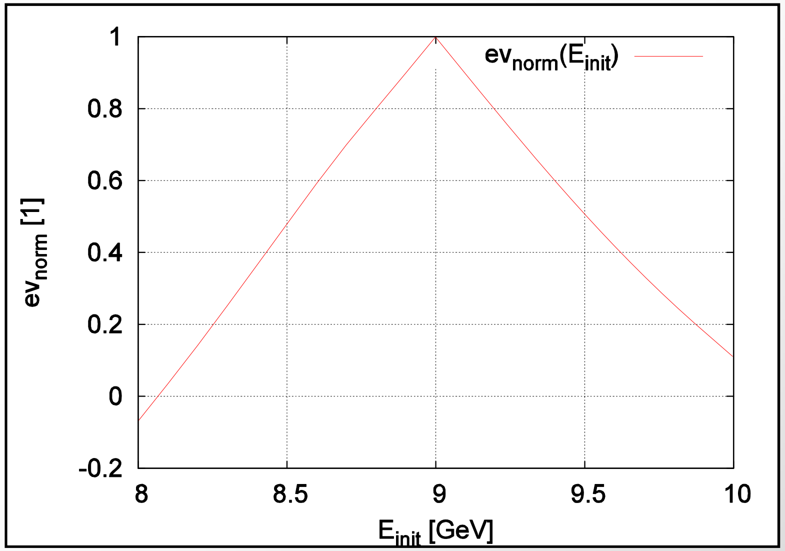
abs_{norm}



Controller works well for:

- abs_{norm} = 0.0 – 0.4

ev_{norm}



Controller works well for:

- ev_{norm} = 0.5 – 1.0

Conclusions

- Controller is so far very robust against disturbances

- However, the influence of coherent ground motion and disturbed measured R could change the picture (simulations to be done).

- Also without simulations we can say, how good the controller performs, with the defined measures.

Planed further work

- 2nd test series with disturbed controller matrix and correct accelerator
- Simulation of controller behavior with ground motion
- Sensibility analysis of the controller in respect to break downs of BPMs
    - Developing of a estimation mechanism to detect BPM breakdowns

Thank you for your attention!