MIMO-LTI Feedback Controller Design
-Status report-

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FLASH Seminar

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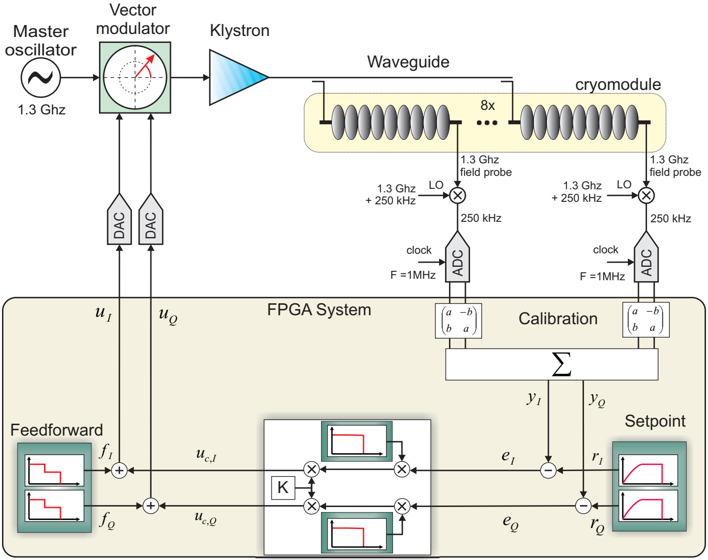
Outline

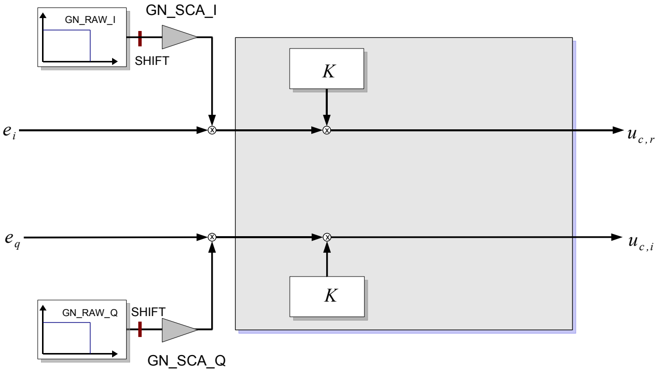
- Current RF Feedback System
  - MIMO controller structure
- System Identification
  - black box modeling
  - model validation
- Fixed order controller design
  - H_∞ design with weighting filters
- Iterative Learning Control
- Outlook

Schematic View of the LLRF Control System



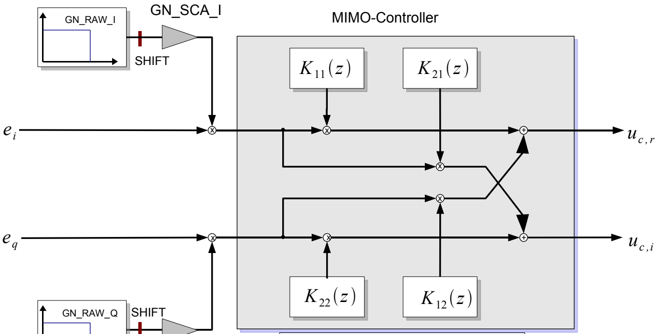
Controller Structure

- so far a decentralized P Controller is used



Controller Structure

- so far a decentralized P Controller is used
- new FPGA implemented controller is given by:



$$K_{ij}(z) = k_{ij} \frac{a_{ij} \cdot z^{-2} + b_{ij} \cdot z^{-1} + 1}{c_{ij} \cdot z^{-2} + d_{ij} \cdot z^{-1} + 1}$$

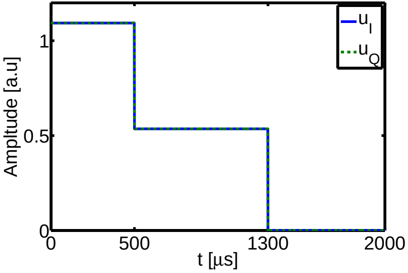
- tuning 20 parameters manually is not possible for users

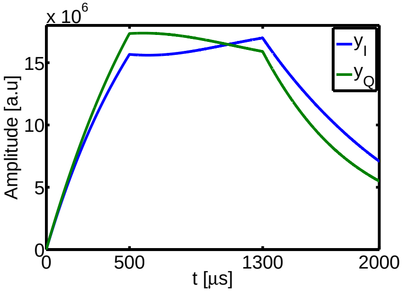
Physical cavity model (LPV)

can be described as a first order lowpass, where the envelope of the electric field is given by the real and imaginary part

$$\begin{pmatrix} \dot{y}_I \\ \dot{y}_Q \end{pmatrix} = \begin{pmatrix} -\omega_{12} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{12} \end{pmatrix} \begin{pmatrix} y_r \\ y_i \end{pmatrix} + R_L\,\omega_{1/2} \begin{pmatrix} u_I \\ u_Q \end{pmatrix}$$

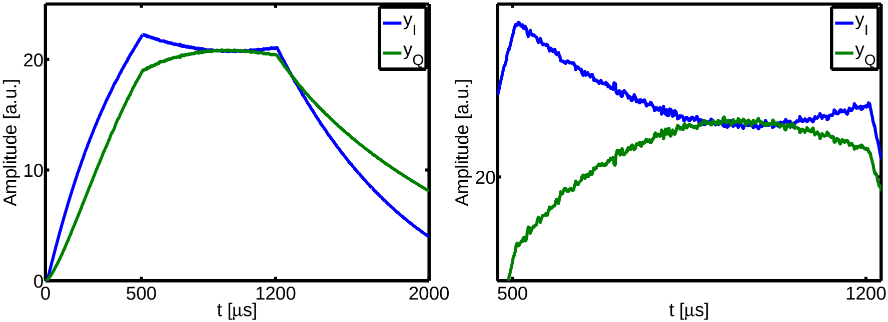
$$\omega_{12} \approx 2\pi \cdot 216\ Hz\ \ ,\ \ \Delta\omega = \omega_0 - \omega\ \ ,\ \ R_L \approx 3.07 \times 10^9 \Omega$$





Open Loop measurements

- real system shows additional dynamics (Sources?)



- disturbances generated from actuator or measurement system
- preamplifier, klystron, microphonics, ...
- downconverter, ADC, VS-Calibration, ...

Estimation of a black box model

The physical model describes the ideal system, but:

- for higher order controller design it might be not sufficient enough
- disturbances and noise effects are hidden
- therefore black box modeling is used

general state space system (LTI)

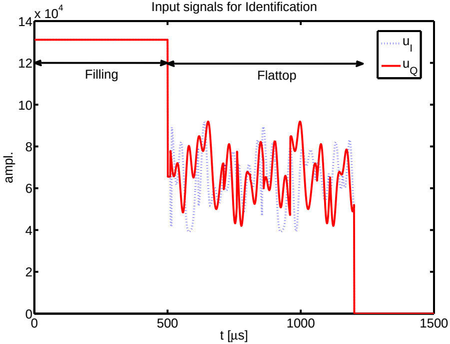
$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}$$

estimating system parameters A, B, C, D with subspace algorithm "n4sid", provided by Matlabs System Identification Toolbox[1]

[1] The Mathworks, *System Identification Toolbox User's Guide*, The Mathworks, Inc., Natick, 2004

Open Loop Identification

For Identification of the system dynamics special input disturbances need to excite the system

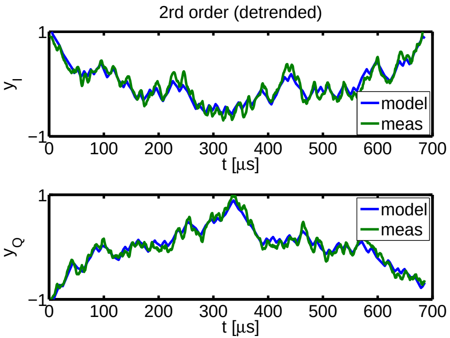


- wide bandwidth (rich enough)
- limited flattop time (max. $800\mu s$)
- good signal to noise ratio (high exc. amplitude)
- excitation close to operation point (low exc. amplitude)

Sufficient model must be found to cover all "real" system dynamics and neglect artificial disturbances

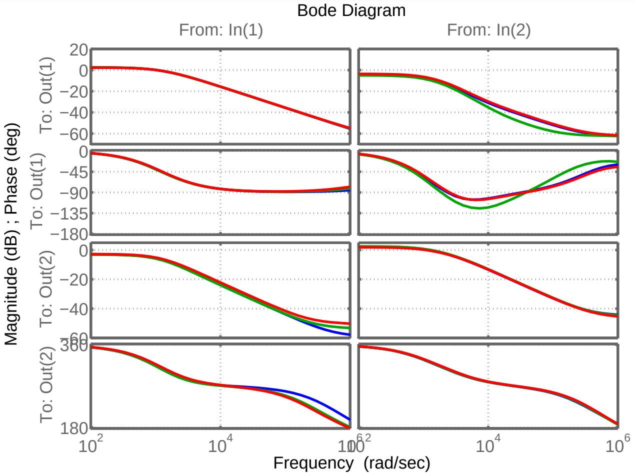
Model validation

Comparing the estimated models during flattop



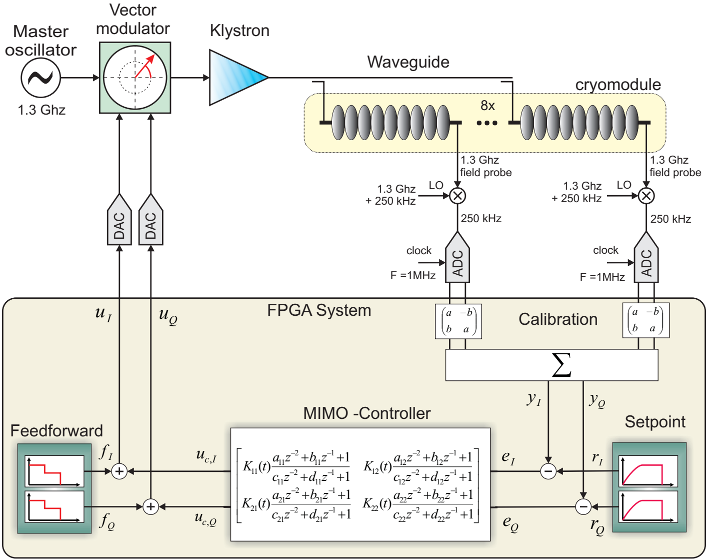
- medium dynamic range can be modeled (cross validation)
- high frequency dynamics are estimated as disturbances
- 3rd order models tend to describe system sufficient

Models Pulse to Pulse



- small variations in the frequency range of interest
- diagonal dominant system (detuning influence smaller)

MIMO-Feedback Control System



Design Objectives

RF field flatness during the flattop is the desired goal

- perfect tracking (reference $=$ output)
  - only possible for low frequencies due to system physics
  - high loop gain (amplifies also disturbances)
  - complementary sensitivity $T(s)$

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RF field flatness during the flattop is the desired goal

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- disturbance rejection
  - high frequency noise is filtered by lowpass characteristics
  - good suppression demands small feedback gain
  - sensitivity $S(s)$

but...

$$S(s) + T(s) = I$$

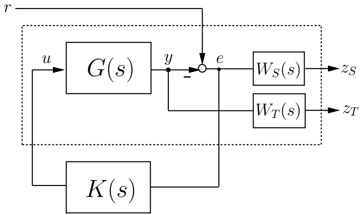
$\curvearrowright$ therefore weighting filters are introduces to shape the closed loop behavior

Generalized Plant with Weighting filters

- using shaping filters to restrict closed loop behavior on fictions outputs of the generalized plant

$$W_S(s) = \frac{1}{M_S}\frac{(s+\omega_{S1})(s+\omega_{S2})}{(s+\omega_{S3})(s+\omega_{S4})}$$

$$W_T(s) = \frac{1}{M_T}\frac{(s+\omega_{T1})(s+\omega_{T2})}{(s+\omega_{T3})(s+\omega_{T4})}$$



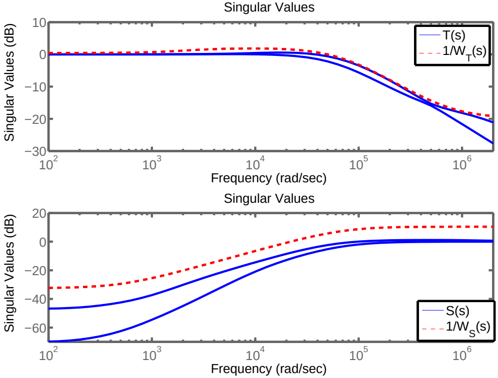
- parameter estimation can be found by solving norm-optimal H_∞ with HIFOO[1]

$$\left\| \begin{array}{c} W_S(s)\, S(s) \\ W_T(s)\, T(s) \end{array} \right\|_\infty < 1$$

[1] J. V. Burke, D. Henrion, A. S. Lewis, M. L. Overton, *HIFOO - A matlab package for fixed-order controller design and H_∞ optimization*, Proceedings of 5th IFAC, 2006

Tuning Weighting filters

Shape closed loop system to desired performance



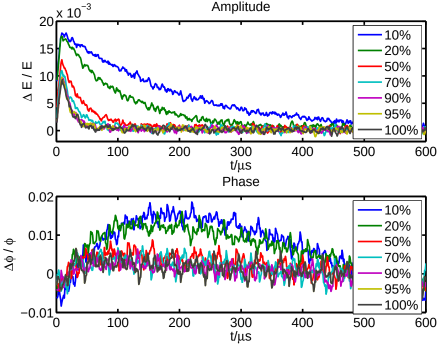
- pulse duration $700\mu s \sim 1kHz$ $\triangleright$ lower limit
- intermediate frequency $250kHz$ $\triangleright$ upper limit

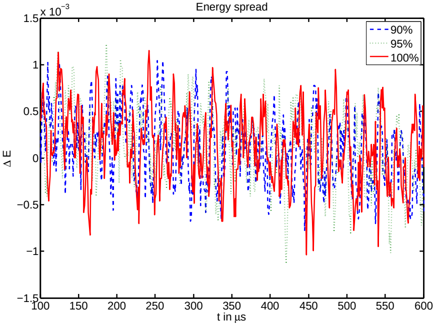
C.Schmidt, G.Lichtenberg, W.Koprek, W.Jalmuzna, H.Werner, S. Simrock, "Parameter Estimation and Tuning of a Multivariable RF Controller with FPGA technique for the Free Electron Laser FLASH", Proceedings of ACC, 2008

First implemented controllers

slow approach (C) to estimated controller gain

$$K(z) = C \cdot \begin{pmatrix} K_{11}(z) & K_{21}(z) \\ K_{12}(z) & K_{22}(z) \end{pmatrix}$$





- highest performance reached so far (1st order)
- instability problems with full order controller parameters
- limited measurement time restricts online tests

Measurement Procedure and Problems

1. Reprogramming the FPGA to use MIMO-Controller
   - set back to operation mode takes time! , parallel system
   - no DOOCS Interface, direct writing into FPGA!
   - testing MIMO-Controller implementation , DONE
2. System Identification
   - algorithms work , investigation of excitation signals
3. Controller parameter estimation
   - unstable higher order controllers , bug found but not verified
   - automatic controller design (under investigation)
   - long term stability proof must be performed
4. Performance test with beam
   - not tested so far because of instability
   - correct gradient/phase settings must be checked (no DOOCS!)

Iterative Learning Control

Adaptive feedforward[3] solving the minimum-norm optimization problem

$$u_{k+1} = arg \min_{u_{k+1}} \{ J_{k+1}(u_{k+1}) : \; e_{k+1} = r - y_{k+1} \, , \; y_{k+1} = G \cdot u_{k+1} \}$$

using the estimated system model (A,B,C) $\longrightarrow$ G

- K is the solution of Riccati-equation

$$\begin{aligned} K(t) \quad = \quad & A^T K(t+1) A + C^T W_1(t+1) C - [A^T K(t+1) B \\ & \times \{B^T K(t+1) B + W_2(t+1)\}^{-1} B^T K(t+1) A] \, W_2^{-1}(t) \, B^T \}^{-1} \end{aligned}$$

- W_1 and W_2 are tuning matrices (tradeoff)

[3] N. Amann, D.H. Owens and E. Rogers, *Iterative learning control for discrete-time systems with exponential rate of convergence*, IEEE Proceedings - Control Theory and Applications, 217-223, 143, 1996

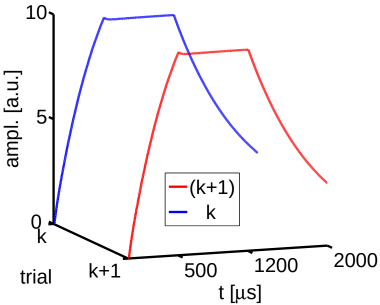
Iterative Learning Control algorithm

computing update input signal as:

$$u_{k+1}(t) = u_k + W_2^{-1}(t)\, B^T \xi_{k+1}(t)$$

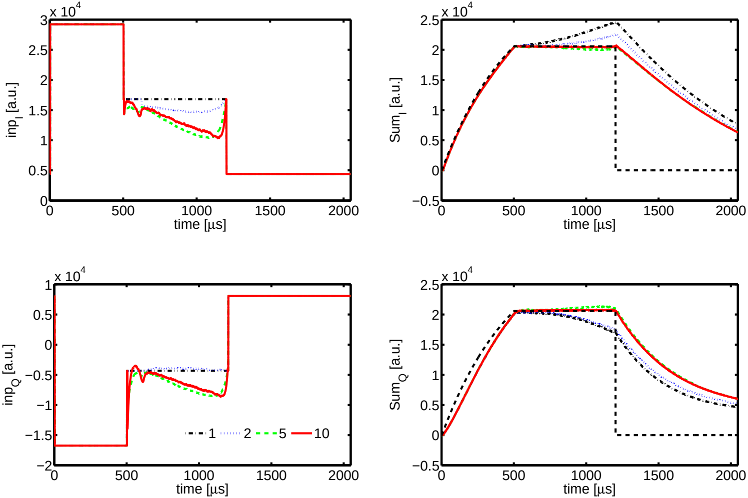
$$\xi_{k+1}(t) = \alpha(t) A^T \xi_{k+1}(t+1) + \alpha(t) C^T W_1(t+1) e_k(t)$$
$$\alpha(t) = \{I + K(t)\, B\, W_2^{-1}(t)\, B^T\}^{-1}$$

- solving non-causal update input
- updates ideally between two pulses
- based on same model



First open loop measurements...

... show promising results



Further developments on ...

...Iterative Learning Control

- currently the updating law is computed with Matlab (SLOW)
  $\curvearrowright$ using C for programming the algorithm
- tests with beam must be performed in next measurements
- exception handling while missing beam !
- closed loop measurements with MIMO or P-Controller

submitted to CDC 2008:

S.Kirchhoff, C.Schmidt, G.Lichtenberg, H.Werner, "An Iterative Learning Algorithm for Control of an Accelerator based Free Electron Laser, 2008"

Summary

- first MIMO-Controller parameters can be estimated
- self updating identification procedure
- self adapting controller parameter
- Iterative Learning controller based on same model
- Automation !

More measurement time needed to test the controller performance for stability with beam!

Special thanks to:
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