First implementation and tests of a Smith Predictor for the LLRF controller at the RF Guns of FLASH, PITZ and EuXFEL.

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Matthias Hoffmann Chicago, October 2, 2019







Overview.

What we expect to see...

- 01 Introduction & Motivation
- **02** Implementation of the Smith Predictor
- 03 First tests at PITZ and EuXFEL
- 04 Optimizing controller settings
- 05 Second tests at PITZ and EuXFEL
- 06 Conclusion & Outlook

Introduction.

The LLRF system for RF guns at FLASH/EuXFEL/PITZ

Laser-driven RF gun based photo injector

- Used at FLASH, EuXFEL, PITZ
- L-Band, 1.3 GHz
- 1.5-cell copper cavity

The LLRF system:

- Down conversion to 54 MHz (IF)
- Sampling with 81 MHz (clock)
- Virtual probe (Forward + Reflected)
- MIMO controller (controlling in I and Q)
- Learning Feed-Forward
- DC IQ drive signal (vector modulator)
- Pulse width modulation

RF pulse structure:

- Repetition rate: 10 Hz
- RF pulse length: 650 us

ector water main solenoid coupler bucking col photo cathode





"Precision Feedback Control of Normal Conducting Standing Wave Resonator Cavity" S. Pfeiffer, et al., PhysRevAccelBeams, 2018

Motivation.

Why do we want to use the Smith Predictor?

RF field stability at FLASH/EuXFEL/PITZ RF gun:

- Large difference in closed-loop performance:
 - PITZ: $\Delta \phi_{rms} \sim 0.1^{\circ}$
 - FLASH/XFEL: $\Delta \phi_{rms} \sim 0.02^{\circ}$
- Comparison of **open loop** data:
 - PITZ: bad $\Delta \phi_{rms} \sim 0.5^{\circ}$
 - XFEL: poor $\Delta \phi_{rms} \sim 0.3^{\circ}$
 - FLASH: acceptable $\Delta \phi_{rms} \sim 0.1^{\circ}$
- PITZ/EuXFEL gun modulator HV stability issue
 - PITZ/EuXFEL: new solid state type
 - FLASH: older bouncer type
- Intra pulse disturbance => fast feedback
- Loop delay ~1.5 us => stability issue at higher gain





The Smith Predictor.

What does it look like?

- Invented 1957 by O.J.M Smith
- Model based/predictive controller
- Dead time compensation
- Two control loops
- Model uncertainty

Sven's Advanced System Setup Tool.

How to find your model?

Features:

- Select facility
- Select subsystem
- System identification
- Controller design
- Learning feed-forward
- Load Smith model

MAIN_GUI@flashlxuser1 - 0 X Version 2.0; © S. Pfeiffer (sven.pfeiffer@desy.de, Tel. 2744) Adjust Fontsize Debug mode **Advanced System Setup Tool** + 0 -System Identification ✓ Write to hardware Welcome sesp0915 at flashlxuser1 IN1 Change user (read) sesp0915 IN2 Define facility, location and module 4000 System Identification/Validation Facility 3000 Module Specify excitation signal 2000 -Exc. unit LLRF.SINCAV DE... -Location 5000 Amplitude ⊖ MV/m hit 1000 DEMO.RF/LLRF.SINCAV DEMO/DEMO/* 10 Offset flattop (samples) (1.1077 us) Define system inputs and outputs PRBS range (0 ... 1) Exc. signal V 11 -1000 🔾 Chirp sine PRBS 0 0.0021 ✓ uQ 🗌 1/10 -2000 CTRL/FFC I.DEMO&FFC O.DEMO Create/plot excitation signal Plot overall excitation signal -3000 Excite and record data 20 Pulse readouts -4000 Specify and adjust time delay Check input Check output Small signal trends Plot small signal/check Td 25 -5000 Remove v(0) Remove v lin, trend Time delay [samples] Plot I/O FFT 700 1000 1100 1200 1300 800 900 2.7692 us Remove glob. trend Time [µs] Specify system model parameters Single-Sided Amplitude Spectrum of U(t) System Model GBM Selection Define and set I/O permanently symmetric O Black Box Model
Grey Box Model 🔾 non-symmetric General Settings GBM Pole Selection Feed-Forward Find system model Low-pass Output Vector Correction Bode model new Fig. Resonant mode Feedback Estimate Low Pass Pole MIMO FE -30 200 f1/2 [Hz] Feed-Forward Correction Learning FF Save system model Save data set demo model 186.7 Bit scaling Save name extension 2 -50 9.028 Sampling freq. [MHz] (e.g. gun, data1, ...) 10 Operating frequency [Hz] -60 Model validation 610.988 649.9779 30.0177 Δ Factor PRBS end Delay [us] Filling [us] Flattop [us] -70 Gen. and plot validation signal -80 Model validation — u(1) - - u(2) -90 104 10⁵ 10⁶ 10^{3} 107 Exit Frequency [Hz]

> "Advanced LLRF System Setup Tool for RF Field Regulation of SRF Cavities" S. Pfeiffer, et al., Proceedings of SRF2019, Dresden, Germany

Optimizing Controller.

Can we make it better?

- Matlab tutorial about "Smith Predictor"
- Simulation used to tune controller settings
- Comparison: PI controller vs. Smith Predictor
 - Set-point tracking: **15 dB**
 - Disturbance rejection: 3 dB

Control of Processes with Long Dead Time: The Smith R2018b Predictor

This example shows the limitations of PI control for processes with long dead time and illustrates the benefits of a control strategy called "Smith Predictor."

Open Script

The example is inspired by:

 A. Ingimundarson and T. Hagglund, "Robust Tuning Procedures of Dead-Time Compensating Controllers," Control Engineering Practice, 9, 2001, pp. 1195-1208.

Process Model

The process open-loop response is modeled as a first-order plus dead time with a 40.2 second time constant and 93.9 second time delay:

s = tf('s'); P = exp(-93.9*s) * 5.6/(40.2*s+1); P.InputName = 'u';

Second Tests at PITZ.

With Optimized Controller

Measurement at the PITZ gun (08/2019):

- Used online tool to tune MIMO controller
- Best Results:
 - Feedback w/ MIMO:
 - Feedback w/ MIMO & Smith Pred.

Conclusion.

Lessons learned & open points...

- No real improvement with the Smith Predictor compared to pure MIMO setup.
- Limited in controller gain and bandwidth compared to simulations
 - Caused by model and/or delay mismatch ?
 - Behavior of Feed-forward vs. Smith Predictor ?
 - Try to match simulations and measurements
- To be checked: Limited by detector resolution ?
- From text books and simulation: *Smith Predictor improves mainly set-point tracking!*

Outlook.

What comes next...

"Advanced Smith Predictor for improved disturbance rejection"

- Additional filter in correction feedback path
- "Approximate inverse of dead time"
- Requires change in controller structure

Huanh, H.-P., et al., "A modified Smith predictor with an approximate inverse of dead time", AiChe Journal, 36 (1990), pp. 1025-1031

1k

10k

100k

frequency [Hz]

1M

Outlook.

What comes next...

Further application for Smith Predictor

- BACCA (Bunch Arrival Corrector CAvity) at FLASH •
 - NRF feedback cavity
 - For longitudinal beam-based feedback ٠
 - Increase actuator bandwidth (0.5 1.0 MHz)
 - Fast set-point changes

Upgrade with BACCA

"Feedback and Synchronization Upgrades at FLASH", S. Pfeiffer, DESY MAC, 2018

DESY. | First implementation and tests of a Smith Predictor | Matthias Hoffmann, October 2, 2019

Thank you for your attention!

Any Questions?

Contact

DESY. Deutsches Matthias Hoffmann Elektronen-Synchrotron MSK www.desy.de +49 40 8998 1670

m.hoffmann@desy.de