System Identification and Robust Control for
the LNLS Fast Orbit Feedback System

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Outline

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LNLS Fast Orbit Feedback Overview

**FOFB Controller**
- PXI-8108
- ~3 kHz loop update rate
- 48 sensor inputs
- 42 actuator outputs

**Fast Archiver**
- 7 days circular buffer (@ ~3 kHz)

**Operator Interface**
- Ethernet LAN
- EtherCAT Network

**Sector #1**
- 4x Bergoz MX-BPM electronics
- 7x Orbit Corrector Power Supplies

**I/O Nodes**
- cRIO-9144
- 100 kHz I/O sampling (16-bit)
- FPGA processing
- CIC decimator (factor 32)
- Controller Dynamics (up to order 24)

**Sector #6**
- 4x Bergoz MX-BPM electronics
- 7x Orbit Corrector Power Supplies
LNLS storage ring orbit stability: within 10% beam size without FOFB

Vibrations: < 2% beam size

Power supply ripple: 5% beam size

FOFB is essential for mitigating undulator (EPU) disturbances

Electron beam sizes (1-sigma) at BPMs:
Horizontal: 870 μm – 1.30 mm
Vertical: 58 μm – 86 μm
System Identification – Model Structure

FOFB Model
System Identification – Model Structure

FOFB Model

- Static Orbit Response Matrices
System Identification – Model Structure

FOFB Model

- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
**FOFB Model**

- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- CIC Decimation Filter + Network Delay

\[ u_{h1} \rightarrow G_{a_{h1}}(s) \rightarrow H_{d}(z) \rightarrow y'_{h1} \]
\[ u_{h18} \rightarrow G_{a_{h18}}(s) \rightarrow H_{d}(z) \rightarrow y'_{h18} \]
\[ u_{v1} \rightarrow G_{a_{v1}}(s) \rightarrow H_{d}(z) \rightarrow y'_{v1} \]
\[ u_{v24} \rightarrow G_{a_{v24}}(s) \rightarrow H_{d}(z) \rightarrow y'_{v24} \]
System Identification – Model Structure

FOFB Model

- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- CIC Decimation Filter + Network Delay
- Magnet Core + Vacuum Chamber
System Identification – Model Structure

FOFB Model

- Static Orbit Response Matrices
- Orbit Corrector Power Supply + Magnet Impedance
- CIC Decimation Filter + Network Delay
- Magnet Core + Vacuum Chamber
- BPM Electronics
System Identification – Experiments

- Pseudo Random Binary Sequence (PRBS)
- One corrector excited at a time
- 62-point PRBS sequence
- 750 Hz bandwidth (-3 dB)
- 9.2 μrad peak-to-peak excitation
- 42 input-output datasets for orbit correctors
- 48 input-output datasets for BPMs
- Input signal spectral lines should not align with output spurious lines
• **Method:** Auto Regressive Model with Exogenous Input (ARX)

• Time-domain average

• **160 sequences** (62-sample long)

• **50% / 50%** of sequences are used for estimation and validation

• Bandwidth of interest: **0 – 500 Hz**
**System Identification – Results**

**Data model validation**

\[ \text{Fit}_\% = 100 \left( 1 - \frac{\|y_{\text{measured}} - y_{\text{model}}\|_2}{\|y_{\text{measured}} - \bar{y}_{\text{measured}}\|_2} \right) \]

<table>
<thead>
<tr>
<th>Orbit Correctors</th>
<th>BPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 97%</td>
<td>&gt; 91%</td>
</tr>
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</table>

**Residual analysis:** no correlation between residues and inputs
Model Uncertainty

Orbit Corrector + CIC Decimator + Network Delay Frequency Response Classes

BPM + Corrector Magnet Core + Vacuum Chamber Frequency Response Classes

Input multiplicative uncertainty:
\[ G_{\text{uncertain}}(z) = G_{\text{nominal}}(z)(1 + W(z)\Delta(z)) \]

Norm-bounded uncertainty:
\[ \|H(\Delta)\|_\infty < 1 \]

Weighting transfer function (order 1):
\[ W(z) \]

- 4 classes for orbit correctors
- 5 classes for BPMs
Control Design – The Approach

Signal-based Control
Detailed characterization of:
• Disturbances
• Noise
• Performance Goals

Robust Control Analysis
• Uncertainty Modeling
• Worst-case analysis

FOFB Control Design

Mixed $H_2/H_\infty$ Optimal Control
• $H_2$ to analyze and optimize performance
• $H_\infty$ to analyze and optimize nominal worst-case
Control Design – Augmented Plant

![Diagram of control system with labeled components:](image)

- **Actuators Inputs**: d \( \rightarrow \) \( W_d \) \( \rightarrow \) u \( \rightarrow \) \( G \) \( \rightarrow \) y \( \rightarrow \) \( W_n \) \( \rightarrow \) n
- **Sensors**: \( W_z \) \( \rightarrow \) z \( \rightarrow \) \( H \) \( \rightarrow \) y'
- **Actual Process Variables**: n
- **Measured Process Variables**: z

- \( W_d \): Unknown disturbance
- \( W_z \): Proper plant
- \( W_n \): Noise
Control Design – Weights

Disturbances Weight

Performance Weight

Disturbances

$W_d$

Performance Channel

$z$

Noise

$W_n$

Noise Weight

$y'$

$u$

$G$

$H$

$y$

$d$

$z$

$n$

$W_z$
Control Design
Performance and Robustness Metrics

\[ r \rightarrow C \rightarrow u \rightarrow G \rightarrow y \rightarrow H \rightarrow y' \]
\[ d \rightarrow W_d \rightarrow W_z \rightarrow z \]
\[ n \rightarrow W_n \]
Control Design
Performance and Robustness Metrics

- EPU gap and phase disturbances
- Power Supplies Ripple
- Beamlines Sensitivity Bandwidth

Diagram:
- C
- G
- H
- W_d
- W_n
- W_z
- r
- u
- y
- y'
- z
- BPMs noise floor
Quadratic cost \((2\text{-norm})\) between normalized input \(d\) + input \(n\) and output \(z\)
Worst-case multivariable gain on sensitivity function

$$\left\| S_y \right\|_\infty$$
Control Design – Simulation Results

\( C(z) = M_C \frac{K \cdot T_s}{z - 1} \)

Tikhonov Regularization on Matrix \( M_c \)

\( \hat{\sigma}_i = \frac{\sigma_i}{\sigma_i^2 + \mu} \)
Control Design – Simulation Results

Controller Structure

\[ C(z) = M_c \frac{KT_s}{z - 1} \]

Tikhonov Regularization on Matrix \( M_c \)

\[ \hat{\sigma}_i = \frac{\sigma_i}{\sigma_i^2 + \mu} \]

\[ \| T_{d,n \rightarrow z} \|_2 \]

\[ \| S_y \|_\infty \]
Control Design – Simulation Results

Optimal Controllers

<table>
<thead>
<tr>
<th>Plane</th>
<th>BW</th>
<th>$|T_{d,n\rightarrow z}|_2$</th>
<th>$|S_y|_{\infty}$</th>
<th>$K$</th>
<th>$\mu$</th>
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</thead>
<tbody>
<tr>
<td>H</td>
<td>25</td>
<td>0.0855</td>
<td>0.7467</td>
<td>19</td>
<td>4e-1</td>
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<tr>
<td>H</td>
<td>50</td>
<td>0.1271</td>
<td>0.7294</td>
<td>10</td>
<td>3e-1</td>
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<tr>
<td>H</td>
<td>10</td>
<td>0.1710</td>
<td>0.7293</td>
<td>10</td>
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<tr>
<td>V</td>
<td>25</td>
<td>0.7837</td>
<td>0.9746</td>
<td>111</td>
<td>1e-2</td>
</tr>
<tr>
<td>V</td>
<td>50</td>
<td>1.160</td>
<td>0.8585</td>
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</tr>
<tr>
<td>V</td>
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<td>1.466</td>
<td>0.8480</td>
<td>62</td>
<td>8e-3</td>
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</tbody>
</table>
Conclusion – LNLS FOFB

- LNLS FOFB performance is fundamentally limited by an overall latency of ~1.5 ms
  - Rule of thumb: 0 dB crossover frequency on disturbance rejection = 1/(20 * closed-loop delay) → ~30 Hz at maximum

- Uncertainty on sensor and actuator transfer functions are relevant only above maximum closed-loop bandwidth (30 Hz) so they cause little harm in practice

- Uncertainty on response matrix does not degrade closed-loop robustness

- Tikhonov regularization “buys” robustness with low degradation of performance

- Simulation results still to be confirmed with experimental data
**Conclusion – General**

- Signal-based control approach makes the loop optimization straightforward.

- Effort should be put on modeling not only plant and sensor, but also disturbance, noise and performance goals.

- Transition from trial and error tuning of FOFB systems to optimization-based techniques allows reaching performance and robustness limits.
Thank you
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Control Design – Simulation Results

Horizontal Plane

Vertical Plane

Singular Values (dB)

Frequency (Hz)

Singular Values (dB)

Frequency (Hz)