Brazilian Synchrotron Light Laboratory

Performance Optimization for the LNLS
Fast Orbit Feedback

Daniel de Oliveira Tavares
Control Engineer at Beam Diagnostics Group
Outline

1. The *Brazilian Synchrotron Light Laboratory* (LNLS)

2. FOFB Hardware Architecture for the LNLS Storage Ring

3. FOFB Systems Overview

4. Correction Algorithms and Orbit Control in Mode Space

5. Actuator Limitations

6. Simulations for performance optimization of the LNLS FOFB

7. Conclusion and Perspectives
## Sirius Project
(in design phase)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Maximum beam current</td>
<td>500 mA</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>460 m</td>
</tr>
<tr>
<td>Horizontal emittance (no ID)</td>
<td>1.7 nm.rad</td>
</tr>
</tbody>
</table>

## LNLS UVX Storage Ring
(in operation since 1997)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation energy</td>
<td>1.37 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>500 MeV</td>
</tr>
<tr>
<td>Maximum beam current</td>
<td>250 mA</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>93 m</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>100 nm.rad</td>
</tr>
</tbody>
</table>
LNLS FOFB – Architecture

- **Acquisition Cell 2**
  - 4 Bergoz MX-BPM per cell
  - 1 kHz bandwidth analog signal
  - 100 kS/s 16-bit data acquisition
  - FPGA processing (filters)

- **Actuation Cell 1**
  - PXI Controller
  - LabVIEW Software
  - 2-3 kHz scan period

- **Actuation Cell 2**
  - 7 PS per cell
  - 100 kS/s 16-bit data acquisition
  - FPGA processing (filters + controller)

---

More details in MO263 – Fast Orbit Feedback System for the LNLS Storage Ring

Performance Optimization for the LNLS Fast Orbit Feedback

Slide 4
**LNLS FOFB – Status**

- Project started on August 2010
  - Labview training (real-time and FPGA platforms)
  - 1 Engineer + 1 Engineering intern
  - Proof of Concept and Bench Tests

- Installation on the Storage Ring on November/December 2010 Shutdown

- First tests with beam in **open-loop** on January 2011
  - Fast acquisition at 3 kS/s (500 Hz bw)
  - Hardware OK
  - Software debugging
  - Setbacks (control system, power supplies)

- First tests with beam in **closed-loop** on February 2011
  - Setbacks (power supplies response)
  - 10 Hz maximum correction rate
LNLS FOFB – Status

• Project started on August 2010
  – Labview training (real-time and FPGA platforms)
  – 1 Engineer + 1 Engineering intern
  – Proof of Concept and Bench Tests

• Installation on the Storage Ring on November/December 2010 Shutdown

• First tests with beam in open-loop on January 2011
  – Fast acquisition at 3 kS/s (500 Hz bw)
  – Hardware OK
  – Software debugging
  – Setbacks (control system, power supplies)

• First tests with beam in closed-loop on February 2011
  – Setbacks (power supplies response)
  – 10 Hz maximum correction rate

Problematic power supply switched off
FOFB Systems - Overview

• FOFB Goal
  – Mitigation of “fast” disturbances, caused mainly by:
    • Magnets vibration (mainly quadrupoles)
    • Power supplies ripple
    • Booster cycles
    • ID gap-phase reconfiguration
    • “Cultural noise” (facility specific)

• History
  – APS pioneer work, 1993: the “real-time orbit feedback” (1 kHz correction rate, 30 Hz effective correction bandwidth)
  – Hardware platform: from control-system-workstation-based to dedicated embedded systems (DSP processor, FPGA) linked by high throughput synchronized network
  – Recently commissioned systems: 4-10 kHz correction rate (global correction), up to 100-250 Hz effective correction bandwidth
FOFB Systems - Overview

• Local vs. Global
  – First systems: multiple local feedbacks in closed-bumps
  – Not desirable in recent 3rd-generation machines → tenths of IDs moving simultaneously

• FOFB vs. SOFB
  – First systems: low- and high-pass filtering to avoid “loop fighting” → generates deadband
  – ALS and SOLEIL had good results downloading SOFB setpoints to FOFB

• Photon BPMs in the loop
  – APS Local Loops
  – SLS local corrections integrated to global feedback
  – SOLEIL’s experience, etc.

• Orbit Control in Mode Space
  – Singular Values Filtering
  – Tikhonov regularization
  – One dynamic controller for each mode? (not yet tried!)

• Actuator Limitations
  – Power supplies (smaller the setpoint step, greater the bandwidth)
  – Vacuum chamber roll-off (most critical for copper and aluminum chambers, not an issue for LNLS stainless steel chamber)
  – Time delay (BPM data filtering group delay, data distribution, correction algorithm processing)
Singular Value Decomposition (SVD)

- The SVD method for matrix “inversion” has replaced MICADO and Harmonic algorithms without performance losses

- Mathematical formulation:
  \[ R = USV^T \quad \rightarrow \quad C = VS_{inv}U^T \]
  Response Matrix \quad Correction Matrix

- Interpretation
  - Low-order modes demands little effort of corrector magnets to correct large distortions
  - High-order modes demands large excursions of corrector magnets for correction small disturbances
  - We must consider the “direction” (making an analogy to the BPM readings as a vector in space) of the disturbance vector

- Filtering the singular values allow to avoid correcting high order modes aggressively
  - Possible approaches:
    - Discard small singular values \(\rightarrow\) information loss \(\rightarrow\) no exact (or maximum) correction anymore
    - Apply Tikhonov regularization (only one degree of freedom; is it the best we can get?)
    - Why not free weighting the singular values, is there any drawback?
SVD Graphical Interpretation

Orbit distortion

Mode space

\[ U^T \]

Correction strength steps

\[ \theta = Cx \]

\[ C = VS_{inv}U^T \]

\[ \theta = VS_{inv}U^T x \]

Dimension loss

\[ S_{inv} \]

\[ V \]
**Eigenvector with Constraints (EVC)**

- *Nakamura et al.* proposes a novel method based on Lagrange multipliers to set constraints of zero error for some BPM readings when “inverting” the response matrix.

- Mathematical formulation:
  
  \[
  A = R^T R \\
  C = DZ - (DB^T - I_n)A^{-1}R^T
  \]

  **Correction Matrix**

  **Response Matrix**

  \[
  A = V\lambda V^T
  \]

  **Eigen decomposition**

  - Equivalent to SVD (minimization of least squares) when calculating the correction matrix without constraints.

  - The eigenvalues of \( A \) are the squared singular values of \( R \).

  - Successful experiences with beam in KEK, ALS and LNLS

Auxiliary matrices:

\[
Z = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 & 0 & \cdots & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 
\end{bmatrix}
\]

\[
B = (ZR)^T
\]

\[
D = A^{-1}B(B^T A^{-1}B)^{-1}
\]
Dynamic Orbit Control

- Traditional Approach

\[ \begin{align*}
  r & \rightarrow e \rightarrow C \rightarrow c(z) \rightarrow p(s) \rightarrow R \rightarrow \hat{h}(s) \rightarrow \hat{h}(s) \\
  & \text{Orbit Controller} \\
  & \quad + \quad + \quad + \quad + \quad + \quad + \quad + \quad + \quad + \\
  & \quad y \\
  & \quad d
\end{align*} \]

- Dynamic Control in Mode Space

\[ \begin{align*}
  r & \rightarrow e \rightarrow U^T \rightarrow S_{\text{inv}} \rightarrow c(z) \rightarrow V \rightarrow p(s) \rightarrow R \rightarrow \hat{h}(s) \rightarrow \hat{h}(s) \\
  & \text{Orbit Controller} \\
  & \quad + \quad + \quad + \quad + \quad + \quad + \quad + \quad + \quad + \\
  & \quad y \\
  & \quad d
\end{align*} \]
Actuator limitation and some ideas...

- The power supplies are always limited in amplitude and slew rate – increasing the step amplitude reduces bandwidth (and linearity)

- Classical approach $\rightarrow$ anti-windup

- It works well for single-input-single-output systems (SISO), but **not for multivariable systems (MIMO)**

- More sophisticated schemes must be investigated.
Preliminary Results

- **Plant Model**
  
  \[ p(s) = \frac{K_{PS} e^{-\theta s}}{\tau_{PS}s + 1} \]
  
  \[ K_{PS} = 1 \]
  \[ \tau_{PS} = 0.5 \text{ ms} \]
  \[ \theta = 1 \text{ ms} \]
  \[ \frac{di}{dt_{\text{max}}} = \pm 0.2 \text{ A/ms} \]

  Vacuum chamber and corrector magnet core ignored → high cutoff on 1.25 kHz (stainless steel vacuum chamber)

  It is assumed that the power supply is regulated by an internal control loop which adjusts the gain according to the setpoint step

- **PI control with anti-windup**
  - Tuning rule (Skogestad):
    
    \[ T_i = \min(\tau_{PS}, 4 \cdot (\tau_{CL} + \theta)) \]
    \[ K_p = \frac{1}{K_{PS}} \frac{\tau_{PS}}{\tau_{CL} + \theta} \]

  \( \tau_{CL} \) is the desired closed-loop time constant

- **Correction algorithm**
  - EVC with 2 constraints (undulator sector)
  - Singular Value Filtering
    - Identification of 3 singular value levels
    - Multiplication by constant factors for each level

---

Performance Optimization for the LNLS Fast Orbit Feedback
Preliminary Results

- Time Response for Step Disturbance
  - SVD linear control
  - SVD with anti-windup
  - SVD with singular value filtering
  - SVD with singular value filtering and anti-windup
  - EVC with 2 constraints, singular value filtering and anti-windup

- Disturbance direction combines higher and lower order modes ("easiest" and "best" direction) with 100 μm of most distorted BPM
Preliminary Results

- **Time Response for Step Disturbance**
  - SVD linear control
  - SVD with anti-windup
  - SVD with singular value filtering
  - SVD with singular value filtering and anti-windup
  - EVC with 2 constraints, singular value filtering and anti-windup

- Disturbance direction combines higher and lower order modes ("easiest" and "best" direction) with 100 μm of most distorted BPM

**After Filtering Singular Values**

![Graph showing RMS COD (mm) and Maximum Current Steps (A) over time for different control methods.](image)
Preliminary Results

• Time Response for Step Disturbance
  – SVD linear control
  – SVD with anti-windup
  – SVD with singular value filtering
  – SVD with singular value filtering and anti-windup
  – EVC with 2 constraints, singular value filtering and anti-windup

• Disturbance direction combines higher and lower order modes ("easiest" and "best" direction) with 100 μm of most distorted BPM

• EVC does not significantly disturb the remaining COD, while guarantying fast disturbance mitigating in the constrained BPMs
Conclusions and Perspectives

PERFORMANCE OPTIMIZATION

- The “Eigenvector with constraints (EVC)” method can provide excellent results, comparable to the SVD, with the additional benefit of providing zero error for the selected BPMs.

- The singular values filtering is essential to increase performance and can also be done inside the EVC framework.

- The control in mode space treats each “disturbance direction” with a different dynamics.

- Simple anti-windup technique is not effective for multivariable systems.

SYSTEM IMPLEMENTATION

- The current LNLS machine will be used as a “test bench” for orbit correction schemes for Sirius.

- The use of commercial hardware allowed quick development → few months with reduced manpower to put the hands on the beam!

- The bottleneck today is the corrector power supplies response (should be replaced until the end of 2011)

FUTURE STEPS (while power supplies were not replaced)

1. Identify the disturbance spectrum
2. Develop new diagnostic tools with the new hardware capabilities
3. Continue to optimize the dynamic control in mode space (simulations)
4. Investigate more deeply constrained control techniques for multivariable systems