Modeling of the SIRIUS Fast Orbit Feedback Control Loop

IBIC 2024, Beijing

L. A. Pelike[1], J. C. S. Carvalho[1], G. R. Cruz[1], A. F. Giachero[1], A. C. S. Oliveira[1], G. S. Ramirez[1], E. N. Rolim[1], F. H. de Sá[1], D. O. Tavares[1]

[1]Brazilian Synchrotron Light Laboratory (LNLS/CNPEM), Campinas, Brazil

Presented by:
Lucas Antonio Pelike

September 11, 2024

LNLS Brazilian Synchrotron Light Laboratory sirius

CNPEM Brazilian Center for Research in Energy and Materials

MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

Presentation Outline

- 4^{th} generation light source located in Brazil
- Storage ring circumference of 518.4 m and 3 GeV electron beam with currently 100 mA (350 mA nominal)
- Fast Orbit Feedback System (FOFB) currently employs 78 Fast Correctors (156 coils) and 80 BPMs (160 BPM readings)
- Orbit disturbance attenuation from 0.1 Hz to 1 kHz
- Update rate of 48 kHz
- In operation for users since 2022
- See article published in ICALEPCS 2023 [1] for technical details
- Objective: build a realistic computational model for the FOFB

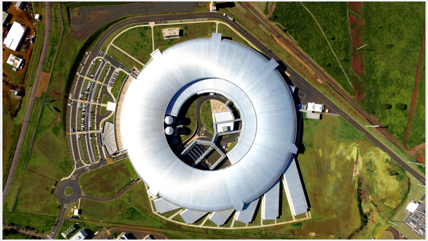


Figure 1: SIRIUS light source

LNLS Brazilian Synchrotron Light Laboratory sirius
CNPEM Brazilian Center for Research in Energy and Materials
MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION
BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

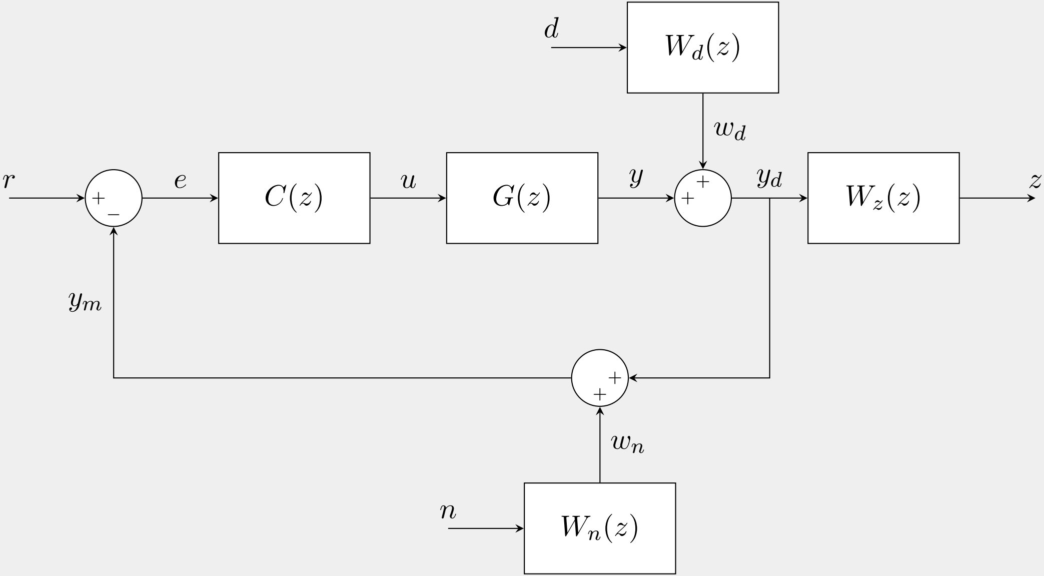


Figure 2: Control loop basic structure

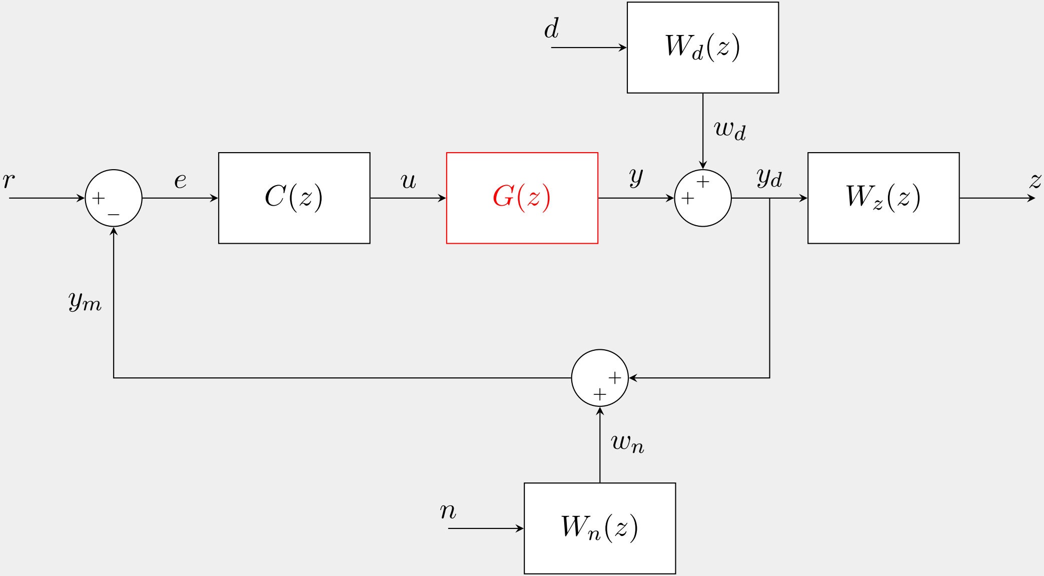


Figure 3: Plant

Plant $G(z)$

Constructed as

$$G(z) = [M \mid \eta] \left[\begin{array}{cccc} A_1(z) & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & A_n(z) & 0 \\ \hline 0 & \cdots & 0 & H(z) \end{array}\right]$$

where M is the measured Orbit Response Matrix, η is the dispersion column, $A_i(z)$ is the model for the i-th corrector and $H(z)$ models the phase to orbit transfer function. The general format for $H(z)$ may be found in [2].

Control Loop Model - Controller

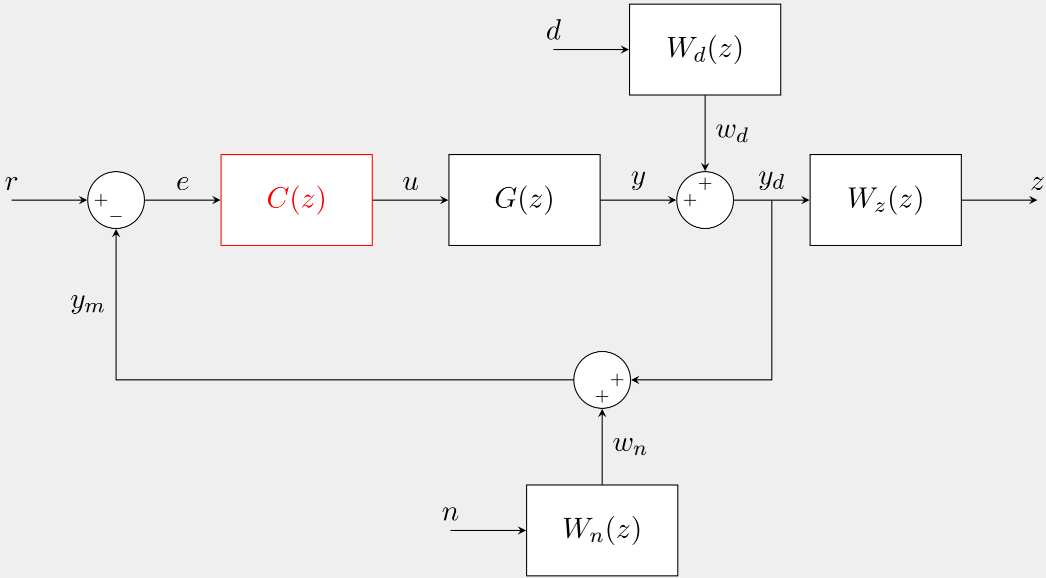


Figure 4: Controller

Controller $C(z)$

Basic integral controller, given by

$$C(z) = F(z)\left(K_I \frac{T_s z}{z-1}\right) M_c$$

where $F(z)$ is an optional shaping filter, T_s is the sample period, M_c is a correction matrix (obtained from the pseudoinverse of the Orbit Response Matrix M) and K_I is a gain matrix, currently defined as

$$K_I = \begin{bmatrix} 0.120 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0.166 \end{bmatrix}$$

LNLS Brazilian Synchrotron Light Laboratory · CNPEM Brazilian Center for Research in Energy and Materials · Ministry of Science Technology and Innovation · Brazilian Government BRASIL Uniting and Rebuilding

Control Loop Model - Weighting matrices

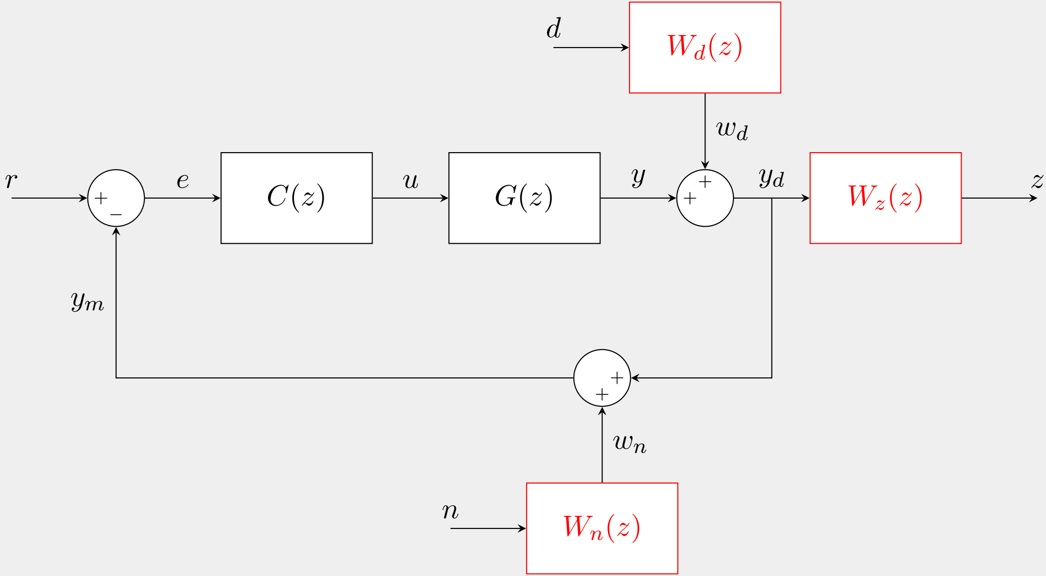


Figure 5: Weighting matrices

System Identification - Experiments

- Actuators' discrepancies motivated system identification experiments
- PRBS derived excitation signals
- Period of $N = 2^7 - 1 = 127$ steps and each applied step is composed of $d = 3$ equal applied samples
- 524 periods collected at a 48 kHz sampling rate and averaged to an equivalent sequence of a period with $Nd = 381$ samples
- Applied to correctors and measured at BPMs (zero gain applied to controller)

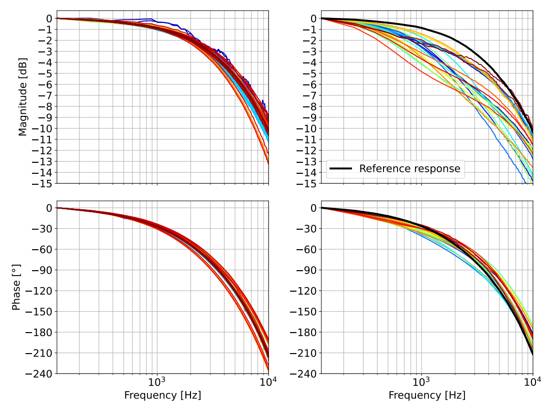


Figure 6: Frequency response of a subset of correctors [1].

- Plant system obtained with fits from experimental data
- Follows basic structure of [3]
- AutoRegressive with eXogenous inputs (ARX) models
- 6^{th} degree polynomials and delay of 2 samples
- Reported fits above 90%
- Builds a system $A_i(z)$ for the i-th corrector. In our case, $1 \leq i \leq 156$

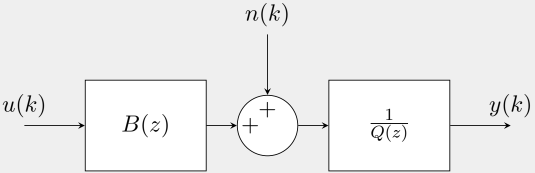


Figure 7: ARX basic structure

Brazilian Synchrotron Light Laboratory
CNPEM Brazilian Center for Research in Energy and Materials
MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION
BRAZILIAN GOVERNMENT UNITING AND REBUILDING

- Excited system's input with PRBS derived signals (parameters N and d)

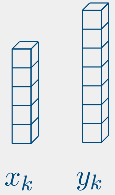


Figure 8: Input and output signals x_k and y_k, at sample $k \in \Lambda$, where Λ is an indexing set with Nd elements.

- Excited system's input with PRBS derived signals (parameters N and d)
- Sequence of matrices obtained from system response and excitation signal

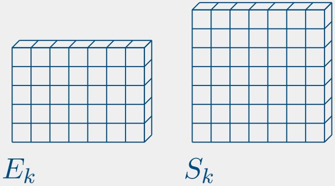


Figure 9: Building matrices E_k and S_k.

- Excited system's input with PRBS derived signals (parameters N and d)
- Sequence of matrices obtained from system response and excitation signal
- DFT of the projection to inputs and outputs of the obtained matrices

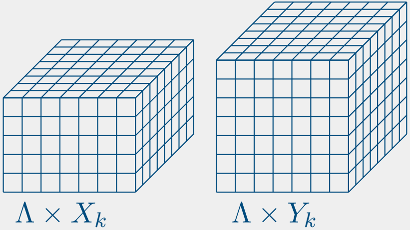


Figure 10: "FFT Cubes" obtained from joining the DFTs of input and output signals as columns.

- Excited system's input with PRBS derived signals (parameters N and d)
- Sequence of matrices obtained from system response and excitation signal
- DFT of the projection to inputs and outputs of the obtained matrices

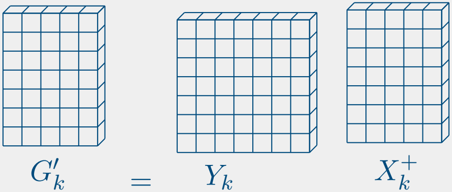
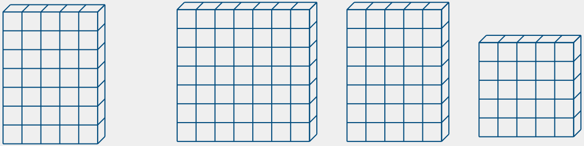


Figure 11: Computation of matrix G'_k evaluated at frequency sample k

Model Evaluation

- Excited each corrector with PRBS derived signals (parameters N and d)
- Sequence of matrices obtained from system response and excitation signal
- DFT of the projection to inputs and outputs of the obtained matrices
- Multiplication by the pseudoinverse and subsequent SVD from the resulting product



$$G'_k = U_{G'_k} \quad \Sigma_{G'_k} \quad V^*_{G'_k}$$

Figure 12: SVD of G'_k

- Excited system's input with PRBS derived signals (parameters N and d)
- Sequence of matrices obtained from system response and excitation signal
- DFT of the projection to inputs and outputs of the obtained matrices
- Multiplication by the pseudoinverse and subsequent SVD from the resulting product
- Allows one to identify singular values in frequency

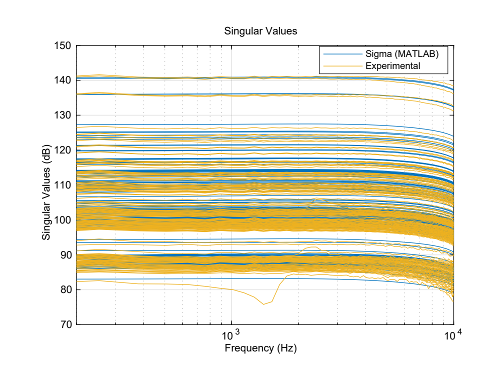


Figure 13: Open Loop singular values

Model Evaluation - Sensitivity (SISO)

- Essentially the same process as described
- Only one corrector and one BPM in the system
- System excitation at BPM readings
- Input signal with an amplitude of $5000\,\mathrm{nm}$
- General agreement between model prediction and experimental data
- Crescent peak around $10\,\mathrm{kHz}$ is a consequence of the chosen d value

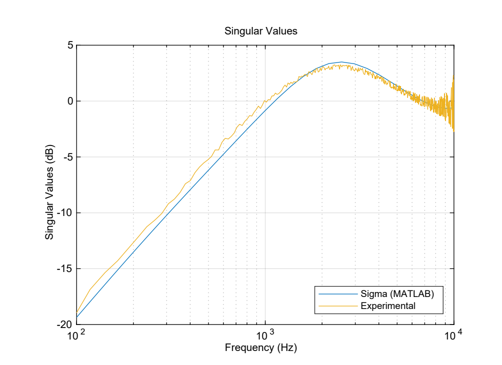


Figure 14: SISO singular values - horizontal

Model Evaluation - Sensitivity (SISO)

- Essentially the same process as in the MIMO case
- Only one corrector and one BPM in the system
- System excitation at BPM readings
- Input signal with an amplitude of 5000 nm
- General agreement between model prediction and experimental data
- Crescent peak around 10 kHz is a consequence of the chosen d value

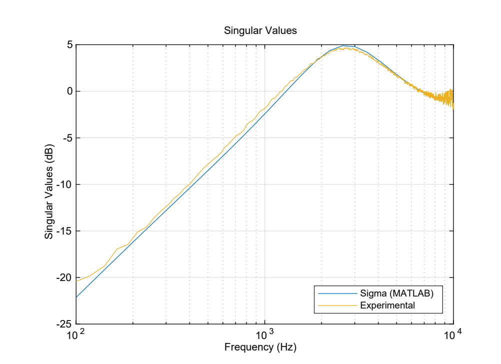


Figure 15: SISO singular values - vertical

- Simulated MIMO sensitivity using the model described
- Comparison between real model (unmatched correctors) and ideal (matched correctors)

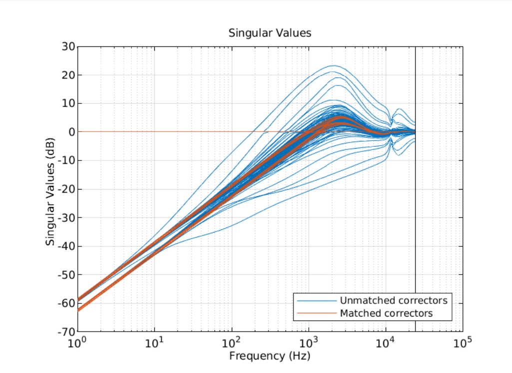


Figure 16: Simulated sensitivity for the obtained model.

Conclusion

- The proposed model allows a realistic analysis of SIRIUS's Fast Orbit Feedback by, for example, capturing discrepancies between fast correctors
- Noise and disturbance inputs allow us to analyze sensitivity and noise rejection for a given configuration
- Robustness considerations could be made by studying gain increases of the model
- An easy-to-use evaluation technique for the model was implemented
- Future work might be concentrated towards a better understanding of the interaction with LLRF loop and optimization tests with shaping filters

References

[1] D.O. Tavares et al. "**Commissioning and Optimization of the SIRIUS Fast Orbit Feedback**". In: *Proc. 19th Int. Conf. Accel. Large Exp. Phys. Control Syst. (ICALEPCS'23)* (Cape Town, South Africa, Oct. 9–13, 2023). International Conference on Accelerator and Large Experimental Physics Control Systems 19. JACoW Publishing, Geneva, Switzerland, Feb. 2024, pp. 123–130. ISBN: 978-3-95450-238-7. DOI: 10.18429/JACoW-ICALEPCS2023-MO3AO03. URL: https://jacow.org/icalepcs2023/papers/mo3ao03.pdf.

[2] P. Kallakuri et al. "**Coupled bunch mode zero correction using orbit measurements and rf system phase feedback**". In: *Physical Review Accelerators and Beams* 25.8 (Aug. 2022). ISSN: 2469-9888. DOI: 10.1103/physrevaccelbeams.25.082801. URL: https://www.osti.gov/biblio/1882009.

[3] D. O. Tavares and D. R. Grossi. "**System Identification and Robust Control for the LNLS UVX Fast Orbit Feedback**". In: *Proc. ICALEPCS'15* (Melbourne, Australia, Oct. 2015). JACoW Publishing, Geneva, Switzerland, 2015, pp. 30–33. DOI: 10.18429/JACoW-ICALEPCS2015-MOC3O04. URL: https://jacow.org/ICALEPCS2015/papers/MOC3O04.pdf.

Thank you!