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IMPLEMENTING NOECO AT NSLS-II*

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Abstract

To characterize the second order (chromatic sextupole) magnetic lattice with high precision (less than 1% normalized residual error), we implemented the Nonlinear Optics from Off-energy Closed Orbit (NOECO) tool based on the Linear Optics from Closed Orbit Modulation (LOCOM) method, named LOCOM-NOECO. Preliminary numerical studies indicate that 1-2% precision can be achieved for the calibration of chromatic sextupoles. This level of accuracy could potentially help in resolving some long-standing challenges of NSLS-II (e.g., the discrepancy between the designed and measured tune shift with amplitude) if such high precision can be attained. Moreover, we implemented the NOECO based on turn-by-turn (TBT) independent component analysis (ICA) for the purpose of independent cross-checking. Both ICA-NOECO and LOCOM-NOECO have been successfully applied to identify the pre-dialled random errors of a chromatic sextupole family, including five power supplies, achieving a residual error of 1% in RMS and less than 2% in peak value.

INTRODUCTION

With the recently implemented lattice tool Linear Optics from Closed Orbit Modulation (LOCOM) [1,2], which combines the precision of LOCO-scheme [3] as well as the speed of multi-frequency AC-LOCO [4], NSLS-II lattice measurement and correction of both linear optics and coupling take only a few minutes. Additionally, LOCOM can characterize linear optics at extremely high chromaticity conditions, significantly accelerating the development of a new operational mode with x/y chromaticity of +10/+10. The high chromaticity lattice could enable reliable operation of the storage ring at high single-bunch currents, crucial for beamline users performing the time-resolved measurements via special timing modes.

To characterize chromatic sextupole errors with high precision, we implemented NOECO [5,6] based on the LOCOM method, named LOCOM-NOECO. Preliminary simulation studies indicate that 1-2% precision can be achieved for calibrating chromatic sextupoles. Achieving such high accuracy could potentially resolve long-standing challenges at NSLS-II, such as discrepancies between designed and measured tune shifts with amplitude.

For independent cross-checking, we implemented NOECO based on turn-by-turn (TBT) Independent Component Analysis (ICA) method [7] (called ICA-NOECO). Both LOCOM-NOECO and ICA-NOECO successfully identified pre-dialled random errors for a chromatic sextupole family of five power supplies, with residual errors of 1% in RMS and less than 2% in peak value, surpassing expectations from numerical simulations.

LOCOM-NOECO

LOCOM Method

Two correctors are used to drive the closed-orbit deviations in each transverse plane to sample linear optics. The betatron phase advance between the two correctors is chosen to be close to $\frac{\pi}{2}$ (modulo π). When the correctors are driven by sinusoidal waveforms and the two waveforms have a proper phase difference, the orbit observed at any BPM also follows sinusoidal waveforms of the same frequency. Therefore, orbit waveforms can be decomposed into two orthogonal oscillation modes, one "sine" mode and the other the "cosine" mode. The amplitudes of these two oscillation modes at each BPM represent the optics information completely [2].

Using a lattice model, mode amplitudes can be calculated [2]. By fitting the quadrupole strengths in linear optics and chromatic sextuple strengths in NOECO in the lattice model, along with corrector gains and BPM gains, the difference between the measured and calculated amplitudes at all BPMs can be minimized in a least-square fashion. By including cross-plane mode amplitudes and adding skew quadrupole strengths in the lattice and the coupling coefficients for the BPM and correctors, the linear coupling errors can be simultaneously determined.

The corrector waveforms used in NSLS-II LOCOM measurements are shown in Fig. 1a. The modulation amplitude in the corrector current setpoint is up to 1 A. An example of raw orbit modulation data for both planes on all 180 BPMs is shown in Fig. 1b. The mode amplitudes for this dataset are plotted in Fig. 1c.

Implement LOCOM-NOECO

Three pairs of LOCOM data and dispersion were measured with 3 different electron beam energies, on-momentum $df = 0\,Hz$ and off-momentums, plus and minus $df = \pm 500\,Hz$.

Instead of fitting the quadrupole strengths in the lattice model, we choose to fit the chromatic sextupole strengths of SM1 and SM2 families by power supplies, totalling 10 variables. The fitted chromatic sextupole strengths normalized by the design values are plotted as the black dotted curve in Fig. 2a. SM1 and SM2 are indexed with 1-5 and 6-10, respectively.

We then added random errors to five power supplies of SM2 family, shown as the blue dashed curve in Fig. 2a. The LOCOM-NOECO tool was applied to obtain the normalized fitted chromatic sextupole strengths, shown as the magenta dotted curve in Fig. 2a. The residual errors were

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calculated as the difference between the magenta and black dotted curves, then subtracted by the added errors represented by blue dashed curve. The results are plotted in Fig. 2b. These residual errors determine the precision of fitting parameters, corresponding to the precision of chromatic sextupole strengths. As shown in Fig. 2b, the sextupole errors are 1% in RMS and < 2% in peak values, exceeding our expectations predicted by the simulation results.

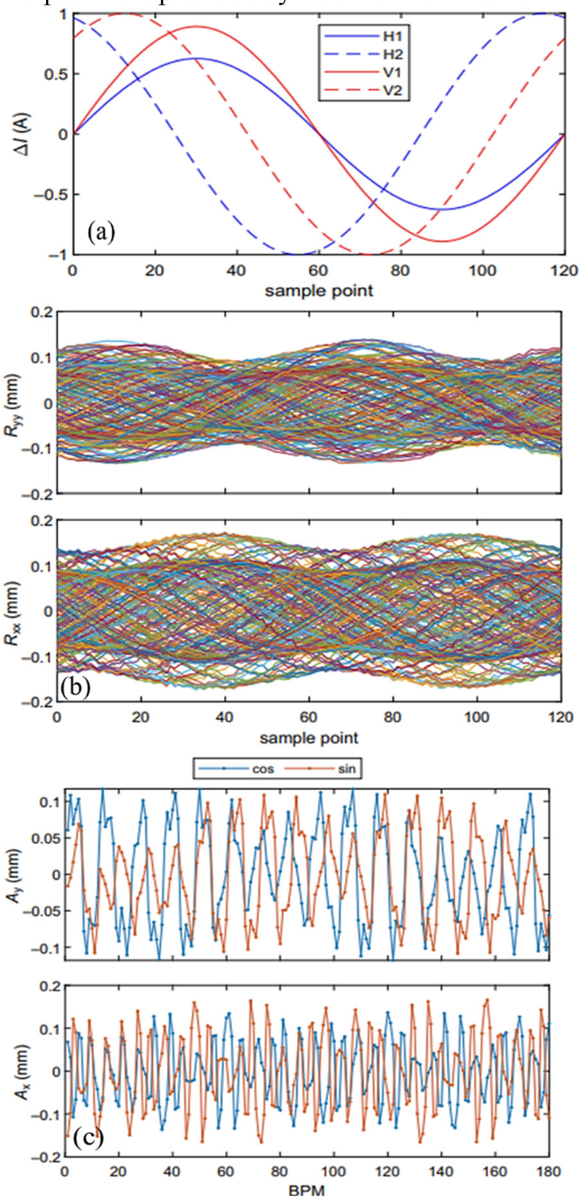

Figure 1: (a) Corrector waveforms used in NSLS-II LOCOM measurements. Horizontal correctors are in blue; vertical correctors in red. The modulation amplitude is 1.0 A. (b) LOCOM data in an NSLS-II measurement. Top: vertical; bottom: horizontal. (c) The horizontal (bottom) and vertical (top) mode amplitudes.

ICA-NOECO METHOD

ICA and Its Application to ICA-NOECO

Based on TBT BPM data, the ICA method is applied to obtain the amplitudes and phase advances of the betatron normal modes, which are compared to their counterparts derived from the lattice model. By fitting the model to the data with quadrupole and skew quadrupole variables, the linear optics and coupling of the machine can be obtained. Experiments on the NSLS-II storage ring show that it can yield the same optics as the linear optics from closed orbit (LOCO) method. The ICA method along with least-square fitting, is applied to obtain lattice and BPM parameters [7].

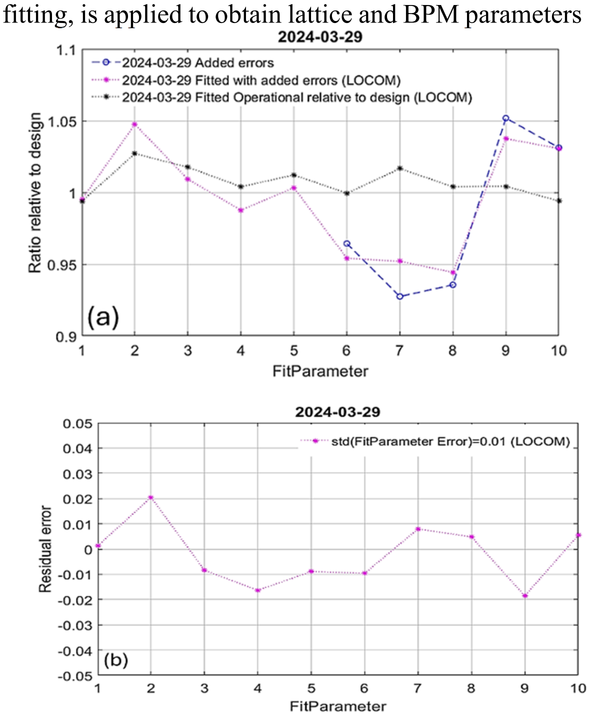

Figure 2: (a) LOCOM-NOECO for operational (black) and error (magenta) lattices; the added sextupole errors are shown as blue circles. (b) Residual errors of fitting parameters.

Three sets of ICA data were collected with 3 different electron beam energies, on-momentum, and off-momentums with $df = 0, \pm 500\ Hz$, simultaneously synchronized with LOCOM-NOECO as shown in Fig. 2. By replacing the quadrupole strengths with chromatic sextuple strengths as the fitting parameters in the lattice model, the difference between the measured and calculated phase advance difference between off-momentum and on-momentum for the betatron normal modes can be used to extract chromatic sextupole strength errors. This tool is named ICA-NOECO.

At the same machine conditions where the LOCOM-NOECO data were collected, we saved the TBT Beam Position Monitor (BPM) data and applied the ICA-NOECO data analysis. Figures 3a and 3b are plotted similarly to Figures 2a and 2b, respectively. As shown in Fig. 3b, the sextupole errors are 1% in RMS and < 2% in peak values, even surpassing the performance of LOCO-NOECO with better precision in identifying the chromatic sextupole strengths. This is likely due to less crosstalk between fitting parameters. The Jacobian size is reduced from 4340×740 (LOCOM-NOECO) to 730×10 (ICA-NOECO).

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Table 1: Detail comparison of ICA-NOECO and LOCOM-NOECO. For LOCOM, the BPM data type is 10 Hz slow acquisition, named 10-Hz SA, and it takes 10 minutes for 3 iterations of the least-square fitting if the saved Jacobian matrix (named *J*) is used; otherwise, it will take 200 minutes for calculating the Jacobian matrix.

NOECO based on	BPM Data Type	Jacobian Size	Residual Error		Time (minute)		Dispersion	Recommend
			RMS	Peak	Data	Process		
ICA	Turn-by-turn	730 · 10	<1%	1%	3	3	Yes	Default tool
LOCOM	10-Hz SA	4340 · 740	1%	2%	10	10-200 (*J*)	Yes	Calibration

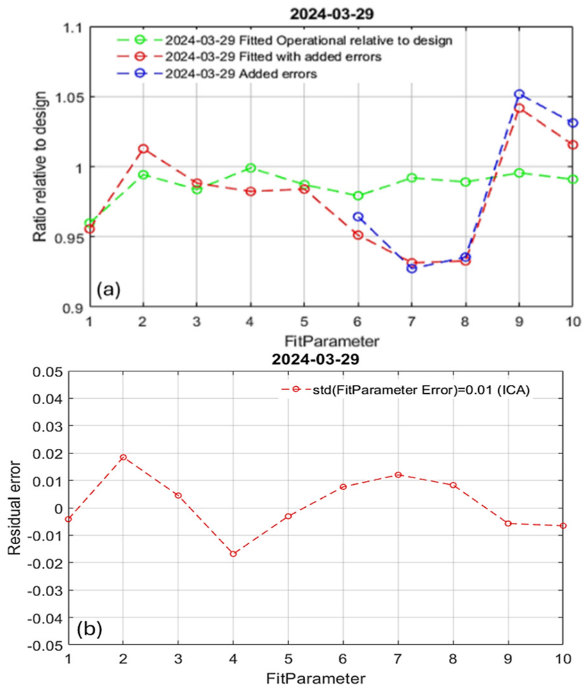

Figure 3: (a) ICA-NOECO for operational (green) and error (red) lattices; the added sextupole errors are shown as blue circles. (b) Residual errors of fitting parameters.

COMPARE ICA- AND LOCO- NOECO

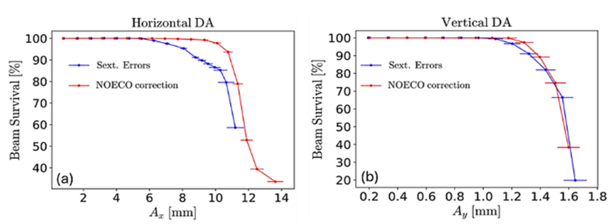

Figure 4: DA measurements before (blue) and after (red) applying the ICA-NOECO correction: (a) horizontal; (b) vertical.

We conducted measurements of the dynamic aperture (DA) by injecting a total of 2 mA beam current into the first 20 buckets of the NSLS-II storage ring. We gradually increased the pinger voltage and recorded the beam current, from which the DA is obtained. Subsequently, sextupole corrections were applied based on the red curve in Fig. 3a and the DA was remeasured. The comparisons for both horizontal and vertical were plotted as Fig. 4a and 4b. It is evident that there is clear improvement in the horizontal DA, but not in the vertical one.

CONCLUSION

We implemented ICA-NOECO and LOCOM-NOECO for NSLS-II storage ring. The preliminary study confirms that the chromatic sextupole strength can be identified with RMS precision better than 1% and a peak error of less than 2%. After applying the sextupole corrections based on NOECO, we observed improvements in both the horizontal DA and the injection efficiency. A detailed comparison between ICA-NOECO and LOCOM-NOECO is presented in Table 1. We recommend using ICA-NOECO for routine nonlinear optics studies due to its smaller dimension of Jacobian matrix. However, if LOCOM-NOECO is chosen, the Jacobian matrix should be saved once and used afterwards; in this case, the calculation speeds are similar for both methods.

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