EXPERIMENTAL CROSSCHECK OF ALGORITHMS FOR MAGNET LATTICE CORRECTION*

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Abstract

Performance, capabilities and limitations of various algorithms for linear magnet optics correction have been studied experimentally at NSLS-II. For the crosscheck, we have selected 4 algorithms based on turn-by-turn beam position analysis: weighted correction of betatron phase and amplitude, independent component analysis, model-independent analysis, and driving-terms-based linear optics characterization. A LOCO algorithm based on closed orbit measurement has been used as a reference. For the correction, either iterative solving of linear problem (matrix inversion with singular-value decomposition) or variational optimization has been used. For all the algorithms, accuracy limitations and convergence of linear lattice correction are discussed.

INTRODUCTION

We have carried out an experimental crosscheck of lattice correction algorithms developed for magnet lattice correction of storage rings. In the early commissioning of NSLS-II [1], we used BPMs turn by turn data to measure the beta beat and correct it from ~30% to ~3% with two different ways, phased advance error correction and beta beat error correction [2, 3]. Even these methods did not include BPMs error, they converged well due to the factor the BPMs gain error is small. We also learned that with very big beta beat, LOCO method distributed error to other error sources and did not work effectively. Later, other different approaches based on turn-by-turn beam position analysis have been studied: weighted correction of betatron phase and amplitude, independent component analysis, model-independent analysis, and driving-terms-based linear optics characterization. These algorithms have been applied for correction of a distorted lattice of NSLS-II and compared with the LOCO algorithm providing the best accuracy.

LOCO

Linear Optics from Closed Orbits (LOCO) has been a powerful beam-based diagnostics and optics control method for storage rings and synchrotrons worldwide ever since it was established at NSLS [4]. This method measures the orbit response matrix and optionally the dispersion function of the machine. The data measured by beam position monitors (BPMs) are then fitted to a lattice model by adjusting parameters such as quadrupole and skew quadrupole strengths in the model, BPM gains and rolls, corrector gains and rolls of the measurement system. According to the fitting result, one can correct the machine lattice to the design lattice by changing the quadrupole and skew quadrupole strengths. The Matlab-based LOCO code [5], which includes many useful fitting and analysis options, is implemented at NSLS-II. Here we use LOCO as a reference for crosscheck of algorithms based on turn-by-turn BPM data analysis.

BETATRON PHASE AND AMPLITUDE CORRECTION

Turn-by-turn data measured by BPMs are used for lattice characterization at many accelerator laboratories for a long time. Spectral analysis of the BPM data with various methods provides measurement of the betatron tunes with high precision, several orders of magnitude better than the simple FFT itself. This leads in turn to a high-precision measurement of the amplitude and phase of betatron oscillation. For NSLS-II, the phase measurement precision is about 0.001 radian. Both amplitude and phase can be used for lattice correction, either independently or in combination with certain weight factors. The main advantage of using betatron phase for lattice correction is that the correction does not depend on BPM calibration. If only the phase is used, the vector of quadrupole strength additions $\mathbf{\Delta K}_1$ required for the lattice correction is obtained by solving the linear equation

$$\mathbf{\Delta\phi} = \mathbf{M}\,\mathbf{\Delta K}_1\,, \qquad (1)$$

where $\mathbf{\Delta\phi}$ is the vector of phase advance errors at the locations of BPMs, which needs to be corrected, $\mathbf{M}$ is the response matrix between the phase advance and quadrupoles' integrated strengths, which is calculated with the design model and the unit conversion coefficients. Similar equation is used for the betatron amplitude correction.

The optics analysis and correction using turn-by-turn BPM data has been implemented at NSLS-II during the machine commissioning [2, 3]. Several iterations of the lattice correction brought the beta-beat down to 3% compared with the designed values. Since the phase advance between adjacent BPMs was corrected, the tunes were shifted to the designed values automatically.

Here we have compared two options: using phase only and using weighted amplitude and phase.

INDEPENDENT COMPONENT ANALYSIS

We experimentally demonstrated the independent component analysis (ICA) method for simultaneous linear optics and coupling correction for storage rings using turn-by-turn BPM data. The ICA method is first applied to extract the amplitudes and phases of the projection of the normal modes on the horizontal and vertical BPMs [6], which are then compared to their model-generated counterparts in fitting. The fitting scheme is similar to the LOCO algorithm [4]. By fitting the model to the data with quadrupole and skew quadrupole variables, the linear

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optics and coupling of the machine can be obtained. Gain and roll errors of the BPMs can be recovered with this method as well. Since closed orbit response and coherent orbit oscillation sample the optics and coupling errors of the machine in a similar fashion, it is expected the performance of this method would be similar to that of LOCO. Simulation results for the ICA method were previously reported in [7], and now it has been confirmed in the experiment. However, the method based on turn-by-turn BPM data is significantly faster than LOCO based on slow corrector variations. The time required to measure an orbit response matrix by LOCO may vary from 10-100 minutes for different machines, while taking the turn-by-turn BPM data can be done within a few seconds only.

DRIVING-TERMS-BASED LINEAR OPTICS CHARACTERIZATION

A new algorithm named as DTBLOC [8] has been recently developed in Python to characterize the linear optics from turn-by-turn data, based on the resonance driving terms (RDTs) for beta-beat and linear coupling [9]. This method requires acquisitions of turn-by-turn data from all BPMs around the ring as well as the dispersion. The real and imaginary parts (or, amplitude and phase) of two frequency components in each plane are extracted by interpolated FFT with windowing (though any high-precision frequency analysis method can be used for this purpose). For NSLS-II, the observation parameters include 1440 values from frequency components (180 BPMs × 2 planes × 2 [primary & secondary peaks] × 2 [real & imaginary]) and 360 values from dispersion (180 BPMs × 2 planes) and 2 values from tunes. The fitting parameters are the integrated strength errors in normal quadrupoles and skew quadrupoles as well as the 4 BPM errors (horizontal and vertical gain errors and roll/crunch deformation errors) for each BPM. The fitting values are estimated via SVD using a Jacobian matrix with analytical expressions based on RDTs. By applying the opposite sign of the fitted magnet strength errors to the machine, simultaneous correction of beta-beating, dispersion, and linear coupling is possible.

MODEL-INDEPENDENT ANALYSIS

Model-independent analysis (MIA) was originally proposed for BPM data processing at Stanford linear accelerator [10]. Then, this method was extended for analysis of one-dimensional and coupled betatron oscillations. For circular accelerators, MIA is a statistical analysis of turn-by-turn BPM data using singular-value decomposition (SVD). This approach uses SVD but it does not require a lattice model. The turn-by-turn beam position measured by M BPMs during N turns is presented as a $M\times N$ matrix **B**. MIA is performed by SVD of the matrix **B**:

$$\mathbf{B} = \mathbf{U}\,\mathbf{S}\,\mathbf{V}^T\,, \qquad (2)$$

where **U** and **V** are orthogonal matrices, and **S** is a diagonal matrix with rapidly decreasing singular values. The columns of the **U** matrix are called the temporal modes of MIA, while the columns of the **V** matrix are called the spatial modes. The spatial mode represents the variation of the temporal mode along the ring.

A lattice correction code based on MIA has been developed at NSLS-II [11]. We have tested this algorithm in comparison with the other ones.

EXPERIMENTAL DATA

To compare the performance and limitations of the lattice correction algorithms, we have created a lattice with a large beta beat by adding random errors to the quadrupoles. This lattice has been used as the initial one to be corrected by every algorithm. R.m.s. values of the errors were $\Delta\beta_x/\beta_x$=8% (horizontal beta function); $\Delta\beta_y/\beta_y$=10% (vertical beta function); $\Delta\psi_x$=4.5° (horizontal betatron phase); $\Delta\psi_y$=3.5° (vertical betatron phase); $\Delta\eta_x$=18mm (horizontal dispersion); η_y=8mm (vertical dispersion). Beta functions and betatron phases have been obtained by spectral analysis of turn-by-turn BPM data using FFT refinement algorithms. The BPM offset and roll errors obtained from LOCO have been taken into account.

Figure 1 shows an example of the relative beta beats and Fig. 2 shows an example of the betatron phase errors before and after correction.

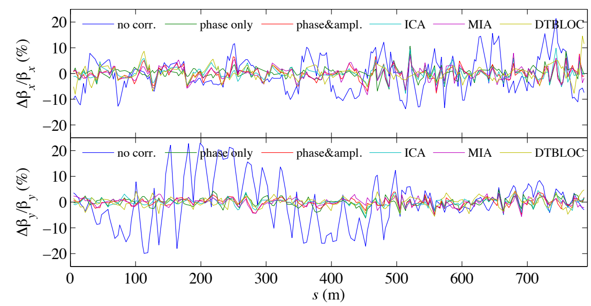

Figure 1: Beta beats before and after correction.

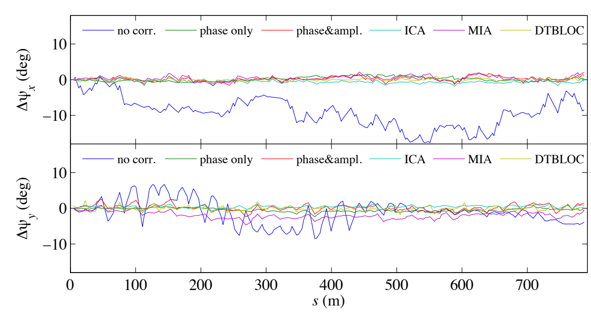

Figure 2: Phase errors before and after correction.

Each correction algorithm has been applied with 3 iterations to the original distorted lattice. The results are summarized in Table 1 showing residual errors of beta function, betatron phase and dispersion in comparison with the initial ones.

Figure 3 and Figure 4 illustrate the convergence of the rection algorithms. These are the residual r.m.s. errors of beta functions and betatron phases as functions of the number of iterations applied. As one can see, all the algorithms are able to correct the lattice quite well, even after only one iteration.

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Table 1: Residual Errors

Algorithm	$\Delta\beta_x/\beta_x$ %	$\Delta\beta_y/\beta_y$ %	$\Delta\psi_x$ °	$\Delta\psi_y$ °	$\Delta\eta_x$ mm	η_y mm
no corr.	8	10	4.5	3.5	18	8
LOCO	2.1	1.4	0.5	0.2	2.6	4.4
phase only[1]	2.3	1.8	0.6	0.5	39	9.9
phase&amp.[1]	2.8	1.7	0.7	0.9	11	7.8
ICA	2.6	1.6	0.5	0.4	5.0	2.3
MIA	2.8	1.7	0.7	1.0	5.4	6.8
DTBLOC	3.0	1.9	0.4	0.8	2.3	4.5

[1] no dispersion corrected

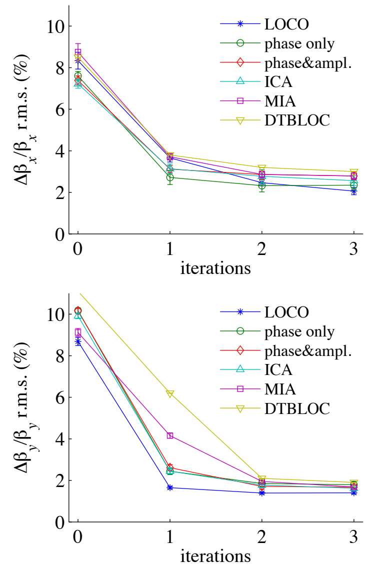

Figure 3: Convergence of beta function: horizontal (upper plot) and vertical (lower plot).

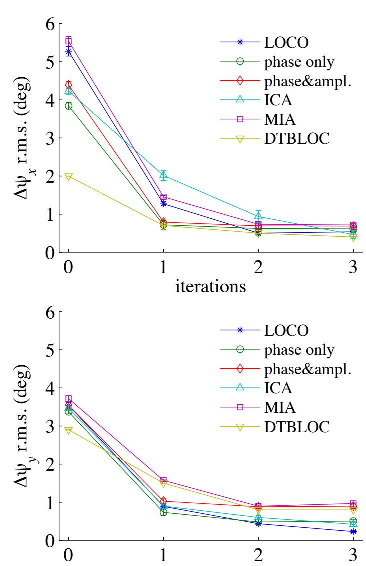

Figure 4: Convergence of betatron phase: horizontal (upper plot) and vertical (lower plot).

CONCLUSION

A crosscheck of 4 algorithms for lattice correction based on analysis of turn-by-turn beam position measured by BPMs has been performed in comparison with the LOCO algorithm based on the orbit response matrix. The measurement results show that the turn-by-turn-based algorithms (weighted correction of betatron phase and amplitude, independent component analysis, model-independent analysis, and driving-terms-based linear optics characterization) provide almost the same correction quality as LOCO, but they are much less time-consuming.

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