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NSLS-II STORAGE RING LATTICE ANALYSIS USING RESPONSE MATRICES*

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Abstract

Affected from various sources, the NSLS-II storage ring lattice is slightly changing operation to operation and, for the operational performance, we are continually optimizing the lattice and maintaining the Response Matrix (RM) for the feedback and lattice analysis. Because not all sources are identified, we are investing efforts to identify them as many as possible. As one of such efforts, we also study the measured RMs. In this paper, we present the results of lattice studies using a pair of recently measured RMs.

INTRODUCTION

As a third-generation light source, in order to provide high-performance synchrotron beam to users, NSLS-II was meticulously designed, optimized and constructed [1]. Especially, a lot of efforts were invested to secure the high-profile storage-ring magnets which satisfy the very strict requirements [2–5].

Even with the satisfactory results of the field measurement and magnet alignment [6, 7], when the magnets were powered by the directly converted currents from the model strengths, the lattice parameters were far from the design values and the lattice needs to be tuned to have optimal design parameters. The deviation from the design with the directly converted magnet power supply currents is not surprising neither making any trouble because there are many tools which can correct the lattice to have the design parameters.

One of the major tools is Linear Optics from Closed Orbits (LOCO) [8]. The original LOCO utilized the Gauss-Newton optimization algorithm and it was improved by adding the Levenberg-Marquardt algorithm [9] and also adding constraints as weights [10]. LOCO is a well established tool being proven by contributing to the lattice optimizations of numerous light sources. NSLS-II also applies LOCO as one of main tools for characterization and correction of the lattice [11]. Furthermore, LOCO parameters can include all the imaginable sources and, by fitting them all together, the lattice can be approach to the desired one.

It is evident that the parameter optimizations like LOCO can correct the lattice and make it more close to the designed model but, unfortunately, it is not guaranteed to correct the deviation source. The main purpose of these tools is compensate the deviation using the well-know control parameters and identifying the real source of deviations is not a simple task [12]. Therefore, the parameters correcting the lattice is frequently changing and it is closely related to the reproducibility issue.

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NSLS-II is implementing MAchine Snapshot Archiving and Retrieve (MASAR) [13] which is a snapshot archiving and retrieving system connected to NSLS-II Experimental Physics and Industrial Control System (EPICS). Each snapshot is a group of key-value pairs where keys are EPICS Process Variables (PVs). The snapshots are organized by configurations where each configuration has specific PV sets. The main purpose of MASAR is by maintaining various machine configurations, making the best lattice be provided at the given situation. MASAR is very helpful and a critical system in satisfactory beam service but does not guarantee reproducing the lattice.

The lattice reproducibility is important because of the consistent beam service as well as it can mean that the affecting elements on the lattice is understood quite well. Even with some efforts [14, 15], the optics reproducibility issue of NSLS-II storage ring has not been resolved. As an another effort, we studied the measured RMs using the parameter optimization to figure out the reproducible portion quantitatively. In NSLS-II, when the machine is turning on after the regular shutdown we measure the RMs for the operation lattice as well as the bare lattice, i.e. with all the insertion devices open. Here, we studied 2 bare lattice RMs measured on July 4 and October 19, 2020. We chose bare lattice to simplify the analysis and also did not consider the coupling components because the there is no coupling in the designed model. By assuming, there should be consistency between these measurements in the deviations from the expected lattice, we estimated them using the quadrupole field error and sextupole alignment errors, which are main sources of linear lattice deviations, control parameters. In the optimization, we used only the selected reliable elements instead of all the components of the RMs. The selecting and optimization processes are described in the following sections.

R-SQUARED OF THE RM ELEMENTS

In NSLS-II, we are utilizing middle layer python library called Accelerator Physics High Level Application (APHLA) [16] and the library is also used for the RM measurements. The input parameters for the RM measurement can be various and APHLA measurement tool is flexible enough to adjust all the parameters. The default APHLA values for the parameters are considered to be chosen as the optimal values and the default values are used always for the measurements.

APHLA RM measurement tool scan the range of ±2 A for each corrector with 4 steps, that makes the step change of the corrector be 4/3 A. For each step the beam position at all Beam Position Monitors (BPM) together with the corrector read-back current values are read 8 times. Therefore, for

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each pair of corrector and BPM, we have 32 data points and the RM element for the pair is obtained by the slope through the linear regression. The results as well as all the raw data are saved in a structured hdf5 file format [17].

NSLS-II has 30 cells with DBA lattice. Each cell has 6 correctors and 6 BPMs working in both planes. Therefore, the element number of the full RM is 360×360. The number is huge but the order of the number is more or less similar for usual storage ring light sources around the world. The number is required because the correctors and BPMs should cover the betatron oscillations around ring to work properly.

The huge number of the elements is the strong point that can enable the RM as a useful diagnostic tool as in LOCO by fitting the various parameters all together as mentioned before. Some correctors and BPMs identified as bad ones are removed, but the portion in the total number is usually negligible. On the other hand, the large number of elements can be a loop hole because their reliabilities are assumed all equivalent and the large number of parameters are anyway try and will succeed in generating the RM elements very close to the measured ones. As the result, we cannot ignore the possibility that the process makes the lattice more look better than it is actually been corrected. To overcome the ambiguity, we quantified the reliability of each element. There could be several ways to evaluate the reliability of the matched parameters but we evaluate them only using R-squared value in statistics.

The RM components are calculated by the linear regression of the single variable. When the specified BPM reading is y_i for the given corrector current x_i, the linear regression means finding best constant α and β which can explains the measured data with the linear model $\beta x_i + \alpha$, Then, with the deviations from the model, residual ϵ_i, the measured data can be expresses as

$$y_i = \beta x_i + \epsilon_i. \quad (1)$$

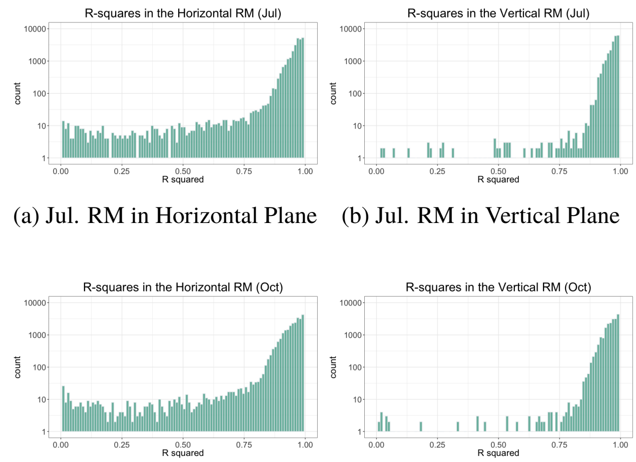
Then the R-squared value becomes

$$R^2 = \frac{SS_{reg}}{SS_{tot}} \quad (2)$$

where, with $\bar{y}$ as the mean value of the data y_is, SS_{reg}, regression sum of squares, is $\sum(\hat{y}_i - \bar{y})^2$ and SS_{total}, total sum of squares, is defined as $\sum(y_i - \bar{y})^2$. The regression sum of squares (SS_{reg}) also can be expressed as

$$SS_{reg} = SS_{total} - SS_{res} \quad (3)$$

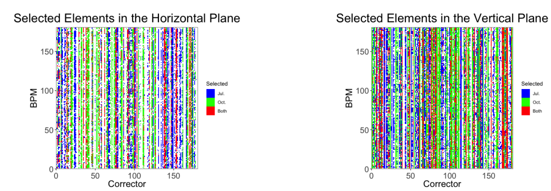
where the SS_{res}, residual sum of squares, is defined as $\sum(\hat{y}_i - y_i)^2$. From the definition, we can say that R-squared value, having $0 \le R^2 \le 1$, can be interpreted as the measure of the model quality by yielding the proportional contribution of the model in explaining the measured data. As an example, 1 as the R-squared value means all the data fit in the linear model.



(a) Jul. RM in Horizontal Plane (b) Jul. RM in Vertical Plane

(c) Oct. RM in Horizontal Plane (d) Oct. RM in Vertical Plane

Figure 1: Distribution histogram of R-squared values



(a) Horizontal Plane (b) Vertical Plane

Figure 2: Selected RM Elements for the Optimization

SELECTED RM ELEMENTS

By applying the linear regression to the 32 raw data for each RM elements measured on July 4 and October 19, we obtained the R-squared for all elements of the RMs. The R-squared values of the measured RMs are shown as the histograms in Fig. 1.

We chose 0.99 as the reliability threshold and performed the parameter optimization using only the selected elements. The numbers of selected elements from the both data set and the portions are collected in Table 1.

Table 1: Number of Selected Elements

Plane	July Meas.	October Meas.	Both
All	21,816 (33.7%)	24,626 (38.0%)	3,823 (11.8%)
$X \to X$	9,117 (28.0%)	9,849 (30.4%)	5,845 (18.0%)
$Y \to Y$	12,744 (39.3%)	14,777 (45.6%)	9,668 (14.9%)

The selected elements are shown in Fig. 2 and we can see the R-squared is strongly dependent on correctors.

PARAMETER OPTIMIZATION

For the parameter optimization, we used, like LOCO, Gauss-Newton algorithm implemented in package *nlsr* [18] of high-level programming language *R* [19].

We are interested in quadrupole field errors and sextupole alignment errors which are considered main sources of the

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deviations of the linear optics. Because we can reasonably assume that there is no correlations between magnets in generating the errors and the resulting deviations cannot be replaced by the errors like corrector scaling and BPM gain errors.

Staring with the model lattice from the magnet power supply currents, we first find the corrector scaling and BPM gain parameters using the measure July RM. Here, the horizontal and vertical plane optimizations are processed independently. Because these optimization is linear, the solution is clear and the process is very fast. It was confirmed that the linear optimization gives the similar improvement also for the October lattice.

Then, with the linear optimization, we optimized the quadrupole field error with constraints for the July lattice. With no constraint or constraints of large ranges, we could achieve significant improvements but these corrections make it worse for the October lattice. We repeated the optimization increasing the constrained parameter range and we checked with October lattice to see the consistency. Quadrupole affects the optics of both planes and we included horizontal and vertical RM elements altogether in the process. The nonlinear optimization is quite time-consuming and we took the step 0.05% of the nominal quadrupole field strength, which can be considered relatively big step. As the quadrupole errors, only 0.15% was allowed to optimize both lattices.

Finally, sextupole alignments were optimized. Different from quadrupole, the effects of the sextupole alignment is not symmetric in horizontal and vertical planes. Furthermore, sextupole mis-alignments bring about the couplings. As the initial estimate, we consider only the horizontal plane and the estimated consistent mis-alignment limit was 500 µm.

CONCLUSTION

If we measure the distance between lattices as the root mean square of the differences in the selected RM elements, the step by step improvements are shown in Table 2.

Table 2: Optimization Results in mm/A

	July		October	
Optimization	**X**	**Y**	**X**	**Y**
None	0.157	0.189	0.129	0.173
Linear.	0.139	0.166	0.106	0.147
Quad	0.125	0.148	0.0914	0.129
Sext	0.113	N/A	0.0798	N/A

Using the measured RMs in July and October, 2020, we estimated the consistent quadrupole field errors and sextupole alignment errors, which are considered the main sources of the linear lattice optics.

The estimated quadrupole field error, 0.15% is consistent with the specification. For the convenient user operation, we correct the orbit not to the quadrupole centers but reference orbit mainly requested by users. Considering horizontal maximum and minimum reference orbits are 320 µm/466 µm, 500 µm order offsets are also reasonable.

The large portion of the deviations is not identified in the study but the algorithm of the study can be applied for further errors giving the lattice deviation.

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