ORBIT RESPONSE MATRIX ANALYSIS APPLIED AT SNS RING

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Abstract

Recently, discrepancies between model-based and observed linear optics, such as the tune and the closed orbit, have been observed in the Spallation Neutron Source (SNS). Accurate accelerator modeling is very important for machine control during the ongoing power ramp up. The Orbit Response Matrix (ORM) method is applied to find and correct errors in the linear optics of the SNS ring. With the closed orbit data (4576 data points), we are able to calibrate the strength of the steering magnets, the BPM gain factors and the 6 quadrupole power supplies. Current results and remaining challenges will be presented and discussed.

INTRODUCTION

The Spallation Neutron Source is a 248 m proton accumulator. It was commissioned 2006 and is currently ramping power to the design value of 1.5 MW. Since a precise accelerator model is very important to machine tune up and beam loss minimization, recently linear optics corrections and beam position monitor (BPM) calibrations were carried out using the orbit response matrix(ORM) algorithm.

Historically, the ORM approach has been used to uncover malfunctioning BPMs, roll angles of magnets, misaligned higher order multipoles and calibration of power supplies in electron storage rings. However its application to the high intensity proton synchrotrons such as the SNS ring is more difficult because of the reduced orbit stability and precision of orbit measurements. Another possible difficulty is the overlap of adjacent magnet fields which could bring large excursion during the fitting process. Fortunately, this correlation problem can now be solved by using a constraint fitting method to get unique solution.

BASIC LOCO ALGORITHM

LOCO is a powerful analytical tool to compute the orbit response matrix and fit it to the model lattice. It was first written by James Safranek to correct the optics of the NSLS X-ray ring [1] and developed later by people at SLAC. Several years ago, LOCO was rewritten in MATLAB [2]. The algorithm of LOCO can be simply described as follows:

If the linear optics in a storage ring is known, then the ORM can easily be calculated. The LOCO algorithm reverses the process. Given the measured orbit response matrix, the code derives the actual linear optics of the ring, including the errors in the optics. Fitting parameters, such as the quadrupole strengths, can then be adjusted to correct the error.

An ORM usually has thousands of elements. Take the ORNL SNS ring as an example, the 44 ring BPMs (dual-plane) and 52 dipole correctors produce 4576 data points. The agreement between the model and the real machine is described by a merit-function $\chi^2(p)$ [5]:

$$\chi^2(p) = \sum_{ij} \left(\frac{\mathbf{M}_{ij}^{\mathrm{meas}} - \mathbf{M}_{ij}^{\mathrm{model}}}{\sigma_i} \right)^2 \qquad (1)$$

where σ_i is the measured noise level on the i^{th} BPM.

Finding the best fit optics model simply requires minimizing the single function, χ^2. Two commonly used minimization search algorithms are Gauss-Newton with weight and Levenberg-Marquadt minimization. The later one is prepared when the problem is too nonlinear. For the analysis of the experimental data in January 2008, we use the weighed Gauss-Newton method to perform the optimization.

The measured ORM needs to be corrected to take into account the imperfections of the measurement systems, e.g. the BPMs and the correctors. The correction parameters include gains and rolls of the BPMs, kick strengthes and tilts of correctors, and the momentum deviation due to the horizontal correctors. For the experiment in January, the fitting parameters in the lattice model are the quadrupole power supplies, the BPM gains and the corrector strengths; this gives a total of 129 parameters, excluding the malfunctioning BPMs and correctors.

Since coupling between LOCO fit parameters can cause excursions of the solution in unconstrained directions, it is natural to put a penalty on such excursions, which brings the χ^2 to the following new format [3]:

$$\chi^2(p) = \sum_{ij} \left(\frac{\mathbf{M}_{ij}^{\mathrm{meas}} - \mathbf{M}_{ij}^{\mathrm{model}}}{\sigma_i} \right)^2 + \frac{1}{\sigma_{\triangle K}^2} \sum_k w_k^2 \triangle K_k^2 \qquad (2)$$

where $\sigma_{\triangle K}$ is an overall normalization constant and w_k^2 is an individual weighting factor to constrain the corresponding quadrupole.

In the analysis of the January experiment, we found large excursions of the solutions without constraint, and therefore we have to put penalties on the quadrupoles to get a reasonable fit.

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MEASURED RESPONSE MATRIX

For a proton storage ring, the resolution of BPMs is much more limited than that of for the electron ring. The noise level is obtained by using the standard error from the sinusoidal fitting of BPM turn-by-turn data. The average BPM noise level is 0.69 mm while the amplitude of oscillation is $15 - 20$ mm.

Before calculating the ORM elements, the malfunctioning BPMs and correctors should be eliminated. Standard errors of sinusoidal fitting are estimated for each BPM data set corresponding to every kick angle. The error distribution of the measured data set is plotted in Figure 1.

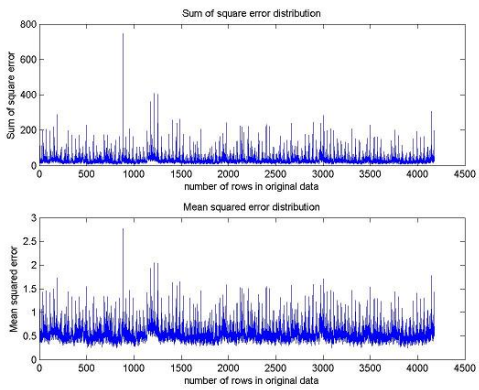


Figure 1: Standard errors from sinusoidal fitting of BPM turn-by-turn data, periodic peaks may reveal malfunctioning BPMs.

The SNS ring has 44 BPMs and 52 dipole correctors available for ORM measurement. Excluding 5 missing correctors and 6 malfunctioning BPMs, the full size of ORM will be 76×47, i.e. 3572 data points. Each ORM element is measured by applying five different kick angles and measuring the corresponding beam orbits. The slope of orbit versus kick angle is obtained by linear least square fitting and is turned into ORM element. The uncertainty levels of the elements are estimated using the norm of the residuals $\sqrt{\sum_i (y_i - y_{pi})^2}$ of linear fitting. The maximum kick angles are 0.53 mrad in both directions, resulting in maximum orbit changes of 10 mm and 4 mm, respectively. The average error sigmas are $0.13\mathrm{m/rad}$ for $\mathbf{M}_{xx}$, $0.09\mathrm{m/rad}$ for $\mathbf{M}_{zx}$, $0.11\mathrm{m/rad}$ for $\mathbf{M}_{xz}$ and $0.09\mathrm{m/rad}$ for $\mathbf{M}_{zz}$. The betatron tune is measured by BPM turn-by-turn data, which gives 6.22 (H) and 6.19 (V) compared to the model predicted value of 6.39 (H) and 6.34 (V).

PRELIMINARY LOCO FITTING RESULT

The SNS ring model contains all up-to-date machine parameters, including the experimental setting of magnets. The ORM data is taken with triggered beam pulses every 1.5 seconds, each with a kinetic energy of 845 MeV and a revolution frequency of 1 MHz. The constrainted fitting is applied and reduces the normalized χ^2 from 10.74 to 2.2,

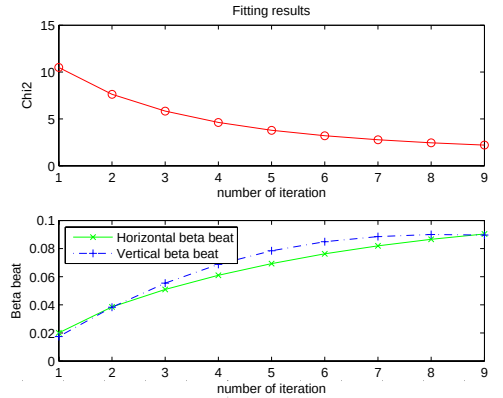
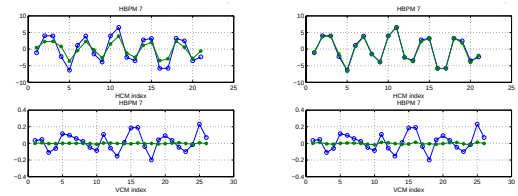


Figure 2: χ^2 and beta-beat for 9 fitting iterations.



(a) before (b) after

Figure 3: Comparing model and measured ORM elements for BPM B07 before and after fitting. The deviations before fitting are mostly from quadrupole gradient errors.

as shown in Figure 2, where beta-beat represents standard deviation of the fractional change of betatron function.

We temporarily removed all the skew quadrupoles from the model and hence excluded BPM coupling factor and corrector rolls from the fitting parameters, which leaves the coupling plane unfitted. The preliminary fitting parameters are 6 groups of 52 gradient errors, 76 BPM gains, and 47 corrector kicks. We found that the major contributors are the gradient errors.

Figure 3 compares the model with the measured data before and after the ORM fitting, for ORM at all correctors' location corresponding to a BPM.

Figure 4 gives the result of 52 gradient errors. Since we grouped the quadrupoles into 6 power supplies, the order of the errors is listed by group, not by position. The error of a power supply is evaluated by averaging the quadrupoles subscribed to it. Therefore, we get 0.56% of error for QV11a12 (1^{st} group, 1-8), -0.7% for QH10a13 (2^{nd} group, 9-16), -2% for QV01a09 (3^{rd} group, 17-24), -1.7% for QH02a08 (4^{th} group, 25-32), -1.7% for QV03a05a07 (5^{th} group, 33-44), and -1.3% for QH04a06 (6^{th} group, 45-52).

Since we did not measure the dispersion and hence excluded it from the fitting parameter list, we are not able to de-couple the BPM gains and corrector kicks, i.e., they share a common scale factor such that the absolute value can not be obtained. However, the relative results, or in another word, the patterns, are reliable, as shown in Figure 5.

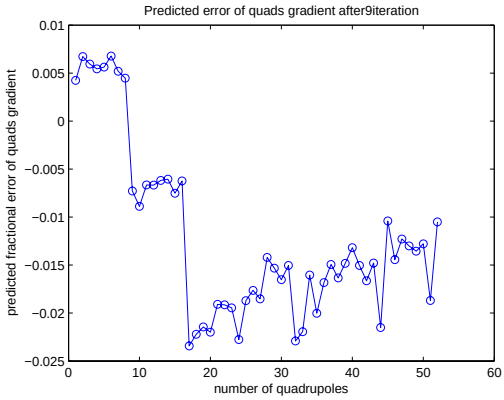
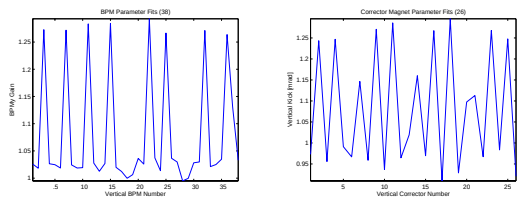


Figure 4: Fitted result of gradient errors in group order : 6 groups and 52 quadrupoles.



(a) Fitting result of the vertical BPM gain factor

(b) Fitting result of the vertical corrector kicks

Figure 5: Fitting result of the gains of BPMs and Correctors : what causes such a pattern?

Interestingly, the corrector strengthes share the same pattern as the BPM gains, which implies that the 3^{rd} and 7^{th} BPMs/correctors on each superiod are not calibrated well during the experiment. Unfortunately, we will not have the chance to further explore the cause of that pattern.

APPLY THE FITTING RESULTS

Our tight SNS run schedule allowed us to input only the corrected quadrupole gradients and compare the original and corrected tune. The experimental results are encouraging: By changing the current of the quadrupole power supplies, the tune discrepancy (between model predicted and measured) is corrected to half of the original. In detail, the original tune discrepancies are 0.17 in the horizontal and 0.15 in the vertical. The ORM fitting predicted that they would be corrected to 0.03 (Horizontal) and 0.06 (Vertical), while the measured ones (after correction) were 0.09 and 0.06.

The disagreement between ORM predicted and measured horizontal tune discrepancy should be investigated. Also, since the ORM fitting and tune measurement were done at two different ramp-up periods, we may need to squeeze both into the same period.

CONCLUSION

We measured the full orbit response matrix of the SNS ring and fit it to the lattice model. By imposing constraints on correlations between fitting parameters, and by fitting the power supplies instead of individual quadrupoles, we obtained a unique solution for the gradient errors. However, the fitting scheme was not able to uniquely determine the other correction parameters because of insufficient information. From the hardware point of view, these constraints are reasonable inputs, and follow-up experiment confirmed that the gradient errors of the focusing magnets can bring the linear optics closer to the model.

There is still plenty of room to improve the results. For instance, turn on the skew quadrupoles and include the coupling as fitting parameter; measure the dispersion and use it to de-couple the BPM's and corrector's gain. Application of the quadrupole's correction suggests that the main contributors of the discrepancy are the normal quadrupoles. But the situation may change and we might need to do the ORM analysis every time after long maitenance period.

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