MULTI-FREQUENCY AC LOCO: A FAST AND PRECISE TECHNIQUE FOR LATTICE CORRECTION

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Abstract

We developed a novel technique to improve the precision and shorten the measurement time of the LOCO (Linear Optics from Closed Orbits) method at NSLS-II [1]. This technique named AC LOCO is based on a sine-wave (AC) beam excitation via fast correctors typically installed at synchrotron light sources for the fast orbit feedback. The beam oscillations are measured by beam position monitors. The narrow band used for the beam excitation and measurement not only allows us to suppress effectively the beam position noise and also makes simultaneously exciting multiple correctors at different frequencies (multi-frequency mode) possible. We demonstrated at NSLS-II that the new technique provides better lattice corrections and achieves two minutes measurement time in the thirty-frequency mode.

INTRODUCTION

Linear Optics from Closed Orbits (LOCO) [2] is a powerful beam-based diagnostics and optics control method for storage rings. LOCO is based on the measurement of the orbit response matrix (ORM). A small perturbation Δx of the beam orbit is created by varying the strength of a corrector magnet located at the longitudinal position s_0:

$$\Delta x(s) = \Delta x'(s_0)\sqrt{\beta_x(s_0)\beta_x(s)}\,\frac{\cos(|\psi_x(s)-\psi_x(s_0)|-\pi\nu_x)}{2\sin\pi\nu_x} \quad (1)$$

where $\Delta x'$ is the transverse angle kick provided by the corrector, β_x is the beta function, ψ_x and ν_x are the betatron phase and tune respectively [3]. The orbit response vector $\Delta\mathbf{x} = [\Delta x_1, \Delta x_2, \ldots, \Delta x_N]$ to the corrector strength variation is measured by beam position monitors (BPMs), which are distributed around the ring. By repeating this process for every corrector in both horizontal and vertical directions, the ORM with $N \times M$ dimension is measured. Here N is the number of BPMs, and M is the number of correctors. Similarly, by varying the beam revolution frequency f_{rev} with Δf_{rev}, the orbit deviation proportional to the dispersion function $\eta(s)$ at the BPM location, can be also measured and included in the ORM as an $(M+1)$-st column:

$$\Delta x_\eta(s) = -\frac{\eta(s)}{\alpha-\gamma^{-2}}\frac{\Delta f_{rev}}{f_{rev}}. \quad (2)$$

Here α is the momentum compaction factor [3], γ is the relativistic Lorentz factor.

The measured ORM is then fitted to the model ORM by adjusting the model accelerator parameters, such as quadrupole and skew quadrupole strengths, gains and rolls of the BPMs and correctors. Then the lattice model becomes a more accurate representation of the live machine; therefore, based on the fitting result, one can apply corrections to quadrupoles and skew quadrupoles to bring the machine closer to the design lattice.

The main disadvantage of the LOCO technique is that it takes a long time for the measurement and correction. The time varies from 10 up to 100 minutes depending on the size of the machine. As the result, LOCO suffers from systematic errors caused by slow drifts of machine parameters during the measurement, as well as by hysteresis effects of adiabatic (DC) variations of slow corrector magnets. Techniques based on turn-by-turn (TbT) BPM data processing [4] are much faster; however, they do not provide such high precision as LOCO, mainly due to the limited resolution of BPMs in the TbT mode.

In this article, we describe an AC LOCO technique based on a sine-wave beam excitation using fast orbit correctors [1]; this approach was first reported in [5,6]. The authors have managed to reduce the time of Diamond Storage Ring optics correction from 1 hour to 5 minutes. Some early efforts at NSLS-II on the precision ORM measurement with AC excitation were reported in [7]. Here we present a detailed analysis of the noise suppression and accuracy limitations, and experimentally prove that AC LOCO can provide more precise ORM measurement and, therefore, better lattice correction, compared to the conventional LOCO. In addition, we introduce the multi-frequency mode and demonstrate two minutes measurement time for a complete set of LOCO data in the thirty-frequency mode. Finally, we compare the AC LOCO performance with the conventional LOCO as well as with TbT-based algorithms.

At NSLS-II, 90 vertical and 90 horizontal fast orbit correctors have been installed for the fast orbit feedback [8]. For the AC ORM measurement, these correctors are used for a sine-wave beam excitation. Horizontal and vertical beam positions are measured simultaneously by 180 button-type BPMs at 10 kHz sampling rate [9].

We are using a standard synchronous detection technique for the BPM data processing, which is described in detail by our early publication [1]. Since the fast corrector provides a monochromatic sine-wave excitation to the beam, only the noise in a very narrow band around ω_0 contributes to the BPM signal and limits the BPM resolution.

The accuracy of the lattice measurement depends on several factors, such as the response functions of the fast correctors and their power supplies, the noise-limited resolution of the BPMs, systematic errors caused by slow drifts of the orbit and quadrupole power supply stability, and hysteresis of the corrector magnets. Since the fast correctors are driven by a sine wave, the magnets are automatically conditioned (hysteresis effect is removed).

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In addition, in the NSLS-II case the fast correctors are air-core and there is no hysteresis at all.

Therefore, the advantage of the AC LOCO technique is that the effects of orbit drift and hysteresis on the measurement accuracy are negligible, and also the narrow-band beam excitation allows us to efficiently suppress the beam position noise in the measurement.

To achieve better accuracy, it is important to choose the optimal frequency for the beam excitation, with the maximum signal-to-noise ratio. The signal-to-noise ratio depends on the amplitude of the beam oscillation excited by a fast corrector magnet, the maximum field of which is determined by its power supply. Below 20 Hz, the maximum AC amplitude of the power supply is determined by the current limit of 1.2 A; above 20 Hz, it is limited by the ramp rate of 160 A/s; therefore, we cannot effectively excite the beam at higher frequencies.

In order to characterize the entire corrector-to-BPM circuit including the power supply, the corrector magnet with vacuum chamber, the beam, and the BPM electronics, a small-signal frequency response function has been measured. The measured frequency responses are shown in Fig. 1. In the plot, $\langle a \rangle_{\text{meas}}$ is the BPM response to a single-corrector AC excitation averaged over all BPMs. The excitation amplitude is 0.142 A, which is about 12% of the maximum power supply current. The difference between horizontal and vertical response functions below 100 Hz is mainly determined by the lattice functions at the correctors and BPMs. So, the response to the AC excitation is linear up to 100 Hz.

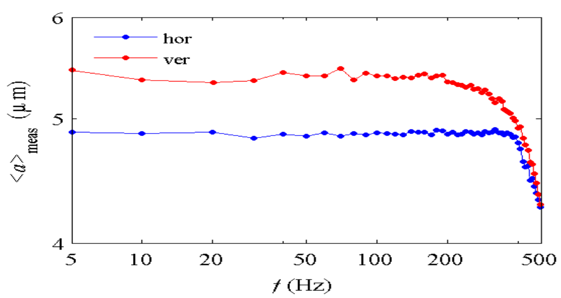

Figure 1: Small-signal frequency response functions: horizontal (blue) and vertical (red).

The noise-limited BPM resolutions have been estimated by analysing power spectral density (PSD) of a series of 180 measurements without any beam excitation. The BPM data were measured during $T = 5$ seconds, therefore the bandwidth is $\delta f = \frac{1}{T} = 0.2$ Hz. The BPM noise is obtained via $\sqrt{\text{PSD}(f_0) \cdot \delta f}$. A separate measurement carried out by the NSLS-II beam diagnostic group gives very similar values of the BPM resolution [10]. The oscillation is excited by one fast corrector at 20 Hz. Using the data measured with and without beam excitation, we can estimate the signal-to-noise ratio.

Beam-based measurements of the frequency-dependent signal-to-noise ratio of the whole system have been carried out at the maximum available amplitude. According to the measurement results, the signal-to-noise ratio exceeds 50 dB in the whole range except two areas around 60 Hz and 100 Hz. The optimal frequency for the best signal-to-noise ratio is around 20 Hz [1].

Figure 2 shows the average noise-induced BPM errors within the measurement bandwidth of 0.2 Hz around 20 Hz. The horizontal and vertical BPM noise graphs show lattice-related patterns with mean values $\langle \varepsilon_x \rangle = 0.016$ µm and $\langle \varepsilon_x \rangle = 0.021$ µm. The total noise is dominated by the beam motion, the actual noise of BPM electronics is much smaller.

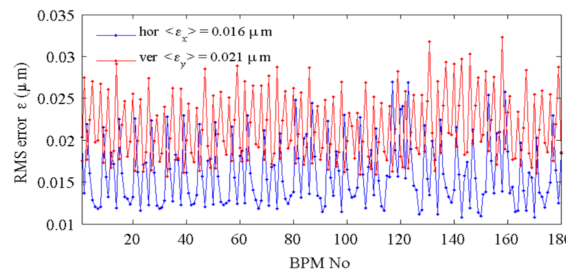

Figure 2: Root mean square amplitude errors at 20 Hz.

The amplitude of beam position oscillation measured by a BPM depends on the values of beta functions at the locations of the BPM and the corrector and on the betatron phase advance between them, according to (1). Example of the horizontal oscillation amplitude measured by all BPMs (blue), which corresponds to one column of the ORM (a single corrector), is presented in Fig. 3, together with the model data (red).

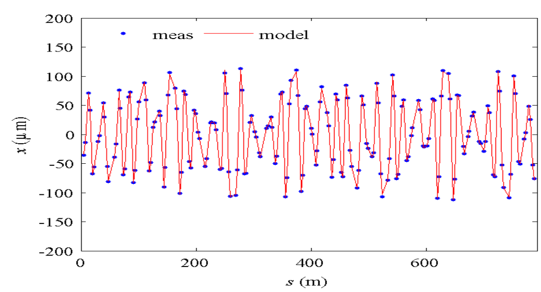

Figure 3: Amplitudes measured by all BPMs at 20 Hz (x).

We numerically investigate how the BPM resolution influences the LOCO fitting results. We found that, if the BPM resolution is below 10 nm, the precision of the linear lattice is mainly determined by the crosstalks between different fitting parameters in the LOCO fitting process. Since the measured noise-limited BPM resolution is close to this number, we can state that the accuracy of the linear lattice correction by LOCO is mainly limited by the systematic error, such as the orbit drift and quadrupole power supply fluctuation during the measurement, etc., not by the BPM resolution.

MULTI-FREQUENCY EXCITATION

Since the signal bandwidth is quite small (0.1 Hz for a 10 second measurement), it provides a unique opportunity to simultaneously excite the beam oscillation via multiple correctors with different frequencies separated by an interval of Δf. This technique can potentially reduce the measurement time down to a minute, which is comparable to the TbT based methods, also with at least an order of magnitude improved measurement precision.

How we choose the frequency range for the multiple excitations is mainly based on the measured frequency-dependent signal-to-noise ratio of the system. We can set the excitation frequency up to 100 Hz still having the beam oscillation amplitude acceptable for the linear lattice correction. Due to the hardware limitation at NSLS-II, only 30 frequency-separated signals are available at the same time for driving the fast correctors. Therefore, the frequency separation Δf is decided to be less than 3 Hz. However, Δf has to be large enough to keep the crosstalk from adjacent excitations below the noise level. The beam oscillation measured by a BPM is a finite-time sine wave, Fourier transform of which is proportional to a sinc function $\mathrm{sinc}(\pi T \Delta f) \equiv \frac{\sin \pi T \Delta f}{\pi T \Delta f}$, where $\Delta f = f - f_0$, f_0 is the excitation frequency. This function has zero values at $\Delta f = k/T$, where k is an integer, so we can choose any of these frequencies for the multi-frequency excitation. In our experiment, $T = 10$ s and $\Delta f = k \cdot 0.2$ Hz, we choose $\Delta f = 2$ Hz. The interference is minimal if we choose Δf multiple of 0.2 Hz.

We have done a prove-of-principle experiment with all available 30 AC driving signals at the time being. The excitation frequencies are 20 Hz, 12 Hz ... 78 Hz, see the spectra of the horizontal and vertical BPM signals (Fig. 4). We repeated the same measurement 10 times in both horizontal and vertical directions to estimate the statistical errors. For each set of the data ($j = 1 \ldots 10$), averaging all BPMs' response to every excitation frequency f_i, $i = 1 \ldots 10$ f_i, we obtain $\langle a(f_i) \rangle_j$. The RMS value over those 10 data sets at each excitation frequency f_i gives the BPM resolution at f_i. In the measurement, we keep the slow orbit feedback on to minimize the slow beam motion. In the excitation frequency range from 20 Hz to 78 Hz, the measured errors are less than 30 nm. We experimentally achieve similar BPM resolutions in the multi-frequency mode compared to the single-frequency mode. The difference of the measured ORMs (multi- and single-frequency) is also within the statistical errors. We did the proof-of-principal experiment via the 30-frequency excitation. By repeating the measurement six times for the total 90 horizontal and 90 vertical fast correctors, a complete set of the ORM was measured in less than 2 minutes.

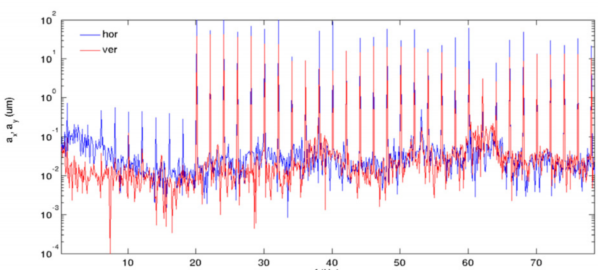

Figure 4: Amplitude spectra of horizontal (blue) and vertical (red) BPM signals.

EXPERIMENTAL RESULTS

The achieved resolution is sufficient to improve the precision of the lattice correction in comparison with the conventional LOCO and others algorithms based on TbT BPM data. To test the performance and limitation of the AC LOCO correction, we have applied the new technique to correct a lattice with large initial beta beat and coupling made by adding random errors to quadrupoles and skew quadrupoles. We have compared the performance of AC LOCO with the conventional LOCO as well as with four algorithms based on TbT BPM measurements. A cross-check of the TbT-based algorithms (weighted correction of betatron phase and amplitude [11], independent component analysis [12], model-independent analysis [13], and driving-terms-based linear optics characterization [14]) has been done in the previous experiment at NSLS-II [4].

AC LOCO gives the best results; three iterations of the AC LOCO correction reduce the beta-beating errors from 10% down to 0.7% [1]. This is at least a factor of two reduction compared with the conventional LOCO technique and close to the estimated beta-beating limit (about 0.4%) determined by systematic errors of the LOCO algorithm and power supply stability limit.

The unique combination of the fast speed (2 minutes measurement time) and high measurement accuracy (30nm) of the multi-frequency AC LOCO could open the door for finding the sextupole alignment error. The preliminary test has been conducted in NSLS-II.

CONCLUSION

A fast and precise multi-frequency AC LOCO technique of magnet lattice correction has been developed and experimentally demonstrated at NSLS-II. In the proof-of-principal experiment at the 30-frequency excitation mode, by repeating the measurement six times for the total 90 horizontal and 90 vertical fast correctors, a complete set of the ORM is measured in less than 2 minutes. Compared to the conventional LOCO, which takes one hour at NSLS-II for one complete set of ORM measurement with a precision of 1 µm, multi-frequency AC LOCO successfully achieves 30-nm precision in the 30-frequncy mode. The significantly improved accuracy of the ORM measurement results in a factor of two reductions in the residual beta function errors of the corrected linear lattice. Based on the LOCO simulation results, the achieved high precision plus high speed could open the door for finding sextupole alignment errors. Besides, the data processing time can be greatly reduced by introducing parallel computing. They will be our future work.

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REFERENCES

[1] X. Yang *et al.*, "Fast and precise technique for magnet lattice correction via sine-wave excitation of fast correctors", Phys. Rev. Accel. Beams, vol. 20, p. 054001, 2017.

[2] J. Safranek, "Experimental determination of storage ring optics using closed orbit response measurements", Nucl. Instr. Meth. A388, p. 27, 1997.

[3] A.W. Chao, K.H. Mess, M. Tigner, F. Zimmerman, *Handbook of Accelerator Physics and Engineering*. Singapore: World Scientific, 1999.

[4] V. Smaluk *et al.*, "Experimental Crosscheck of Algorithms for Magnet Lattice Correction", Proc. IPAC'16, Busan, Korea, May 2016.

[5] G. Rehm *et al.*, "Measurement of Lattice Parameters without Visible Disturbance to User Beam at Diamond Light Source", Proc. BIW10, Santa Fe, New Mexico, US, May 2010.

[6] I.P.S. Martin *et al.*, "A Fast Optics Correction for the Diamond Storage Ring", Proc. IPAC'14, Dresden, June 2014.

[7] W. Cheng *et al.*, "Precise Beam Orbit Response Measurement with AC Excitation", Proc. IPAC'16, Busan, Korea, May 2016.

[8] Y. Tian and L.H. Yu, "NSLS-II Fast Orbit Feedback with Individual Eigenmode Compensation", Proc. PAC'11, New York, March/April 2011.

[9] K. Vetter *et al.*, "NSLS-II RF Beam Position Monitor Update", Proc. BIW'12, Newport News, April 2012.

[10] W. Cheng *et al.*, "Characterization of NSLS2 Storage Ring Beam Orbit Stability", Proc. of IBIC'15, Melbourne, Australia, Sept. 2015.

[11] G.M. Wang *et al.*, NSLS II Commissioning report, BNL Tech. Note 168, 2015.

[12] X. Huang *et al.*, "Application of independent component analysis to Fermilab booster", Phys. Rev. ST Accel. Beams, vol. 8, p. 064001, 2005.

[13] J. Irwin *et al.*, "Model-Independent Beam Dynamics Analysis", Phys. Rev. Lett., vol. 82, no. 8, p. 1684, 1999.

[14] Y. Hidaka and B. Podobedov, "Linear Optics Characterization and Correction Method Using Turn-by-Turn BPM Data Based on Resonance Driving Terms with Simultaneous BPM Calibration Capability", Proc. NA-PAC2016, Chicago, Oct. 2016.