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AN IMPROVED METHOD FOR LINEAR OPTICS AND COUPLING CORRECTION BASED ON CLOSED ORBIT MODULATION *

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Abstract

In this study, we propose an important modification to the processing of the orbit modulation data for the previously proposed LOCOM method and demonstrate the application of the improved method with experiments on a machine. Instead of fitting the individual orbits, the new method decomposes the orbit oscillation into two orthogonal components and fit the amplitudes of the components. This greatly reduces the number of data points for fitting and in turn the size of the Jacobian matrix. It also allows the use of a much larger data sample, such as thousands of orbits collected when the correctors are driven by fast waveforms. In the experiments, the optics correction results are independently verified with turn-by-turn BPM data.

INTRODUCTION

Correction of linear optics and coupling with closed orbit modulation has previously been proposed and demonstrated in simulation [1]. The method is referred to as linear optics from closed orbit modulation (LOCOM). Unlike LOCO [2], which fits the closed orbit responses of many correctors distributed around the ring, LOCOM uses only two correctors. By driving the two correctors with sinusoidal waveforms, the closed orbit deviation can sample the phase space ellipse fully. If fast corrector magnets are used, data taking can be done within seconds. The method also has a number of advantages over methods that utilizes turn-by-turn (TbT) BPM data [3–8]. For example, closed orbit measurements do not suffer from decoherence, which can severely limit the number of usable turns in TbT data, especially when the chromaticity is high.

The original LOCOM method fits the individual closed orbits obtained with combinations of the kicks from the two selected correctors. It works in the much same manner as does LOCO. Because there are many BPMs, the total number of data points used for fitting can be very large when a large number of orbits are included. It is possible that the Jacobian matrix becomes so large such that there is not enough computer memory to perform the calculations. In this study we propose a new method to process the LOCOM data, in which the modulated orbits are reduced to two orthogonal modes for each plane. For each BPM, only 4 mode amplitudes are needed to fit the linear optics and only 8 mode amplitudes are fitted for both linear optics and coupling, regardless of the number of orbits used.

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This method has been demonstrated on the SPEAR3 and NSLS-II storage rings. In the NSLS-II experiments, we performed tests to detect errors intentionally planted in the ring and to correct randomly introduced optics errors. The TbT BPM data, processed with the independent component analysis (ICA), are used to verify the optics correction results. In the next sections, we will describe the new LOCOM method and the experimental results at NSLS-II.

THE IMPROVED LOCOM METHOD

The orbit modulation data used in the new LOCOM method are the same as the original method. Considerations for selecting the two correctors and the phase difference between the waveforms applied to the correctors are also the same. In the original LOCOM method, we choose a number of points on the waveform, each point corresponding to an orbit, for data fitting. However, in the new method, the modulated orbit observed at each BPM is characterized as a sinusoidal waveform. Because the phase advances at the BPMs are different, the observed waveforms have different phases. We can decompose the waveform at all BPMs into two common orthogonal components,

$$\begin{aligned} x_i(n) &= A_i \sin(2\pi\nu n + \phi_i) \\ &= A_{si} \sin 2\pi\nu n + A_{ci} \cos 2\pi\nu n, \end{aligned} \tag{1}$$

where i is the BPM index, n is turn number, ν is the modulation frequency, and A_{si} and A_{ci} are the amplitudes of the sine and cosine modes. The mode amplitudes are connected to the amplitudes and phases of the corrector waveforms and the transfer matrices from the correctors to the BPM. The derivation is straightforward and some details can be found in Ref. [9].

If we choose the modulation tune to be the reciprocal of an integer N, i.e., with $\nu = 1/N$, and uniformly sample N points over a period on the waveform, we can calculate the mode amplitudes from the measured orbits accurately, with

$$\begin{aligned} A_{si} &= \frac{2}{N}\sum_{n=1}^{N} x_i(n) \sin\frac{2\pi n}{N}, \\ A_{ci} &= \frac{2}{N}\sum_{n=1}^{N} x_i(n) \cos\frac{2\pi n}{N}. \end{aligned} \tag{2}$$

Because the mode amplitudes are related to the transfer matrix elements, they can be used to constrain the lattice model in fitting. In fact, the mode amplitudes could be seen as a condensed form of the information represented by the closed orbits. When a large number of sample points are drawn from the waveform for the calculation with Eq. (2),

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the mode amplitudes will converge to a set of well-defined values. Fitting the lattice model with these values is much easier than fitting directly the closed orbits as the number of data points is much smaller; yet there is no loss of information.

Considering linear coupling in the lattice and coupling in the BPMs and the two correctors, the steering modulation in one plane will introduce orbit modulation in both transverse planes. There are four mode amplitudes at one BPM for modulation in one plane. Since we would like to modulate the orbit in both planes, there will be eight mode amplitudes to represent the linear optics and coupling information at one BPM. The measured dispersion functions are to be included as fitting data points as well. Therefore, there are $10P$ data points, where P is the number of BPMs.

The fitting parameters include the same lattice parameters as would be used in LOCO or other optics correction schemes. These typically include a number of quadrupole and skew quadrupole parameters. The BPM gain and coupling parameters should also be included as fitting parameters. The gain and coupling parameters of the four correctors (two in each plane) are also included. There are a total of $N_q + N_{sq} + 4P + 8$ fitting parameters, where N_q and N_{sq} are the number of quadrupole and skew quadrupole parameters, respectively.

The Levenberg-Marquadt method is the ideal least-square fitting method for our purpose. It is simple to add constraints to limit the diversion of the fitting parameters. In linear optics correction, it is critical to prevent the fitted $\Delta K/K$ to drift in the under-constrained directions [10].

EXPERIMENTS ON NSLS-II

In the NSLS-II experiments, we deliberately added errors to the machine and corrected the linear optics and coupling. The results are verified with turn-by-turn BPM data. In the following we present the experiments at NSLS-II to illustrate the application of the method.

In the experiments the correctors are changed step by step on the waveforms, with 120 sampling points over one period. The corrector waveforms for the two pairs of correctors are as shown in Fig. 1. The phase differences between the pairs are chosen according to the phase advances between the two correctors to effectively sample the phase space ellipse [1]. Figure 2 shows an example of the horizontal and vertical mode amplitudes with in-plane modulation. There are 180 BPMs in the ring. The orbit modulation amplitude is only up to about 0.15 mm. However, because the closed orbit can be measured very accurately, the data still give high resolution for optics measurements.

To introduced linear optics and coupling errors to the ring, starting from the operation lattice, the strengths of all quadrupoles were randomly changed by a small amount, with rms $\Delta K/K = 0.01$, and all 30 skew quadrupoles were turned off. We fit 180 quadrupole parameters and the 30 skew quadrupole parameters, along with the gains and coupling coefficients for the BPMs and the correctors. The betatron

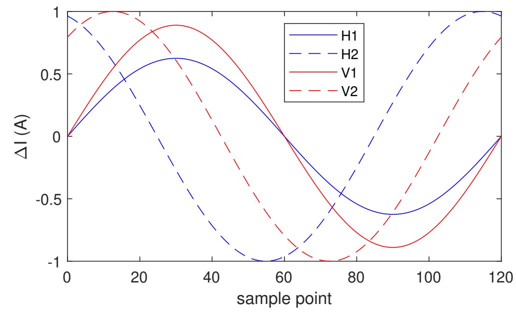

Figure 1: The horizontal (blue) and vertical (red) corrector waveforms used in NSLS-II DC LOCOM measurements.

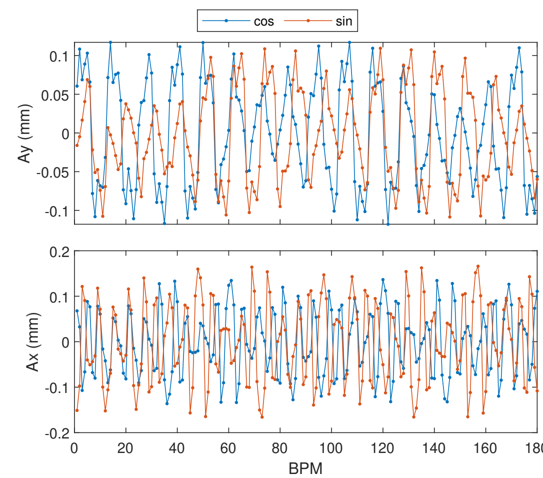

Figure 2: The horizontal (bottom) and vertical (top) mode amplitudes in the NSLS-II DC LOCOM measurement.

phase advances of the fitted lattice are different from the design lattice and the differences represent the linear optics errors. The betatron phase advances can also be measured with turn-by-turn BPM data, using ICA to process the data [3, 8]. Results with the two approaches for the lattice with initial errors are compared in Fig. 3.

The fitted quadrupole errors are plotted in Fig. 4. The beta beating of the fitted lattice is shown in Fig. 5. The initial rms beta beating is 11.5% and 10.1% for the horizontal and vertical planes, respectively. Also shown in Fig. 4 are the fitted skew quadrupole errors. The emittance ratio of the fitted lattice is 2.7%.

The fitted quadrupole and skew quadrupole values were dialed in to correct the errors. Another round of LOCOM data were taken and fitted. The fitted lattice now has rms beta beating of 1.7% and 3.9% for the horizontal and vertical planes, respectively. The large remaining optics errors may be due to magnet hysteresis as large changes were applied. The emittance ratio of the fitted lattice is now only 0.25%.

A second round of correction was applied, followed by taking LOCOM data. The fitted lattice has rms beta beating of 0.8% and 1.1% for the two planes, respectively (see

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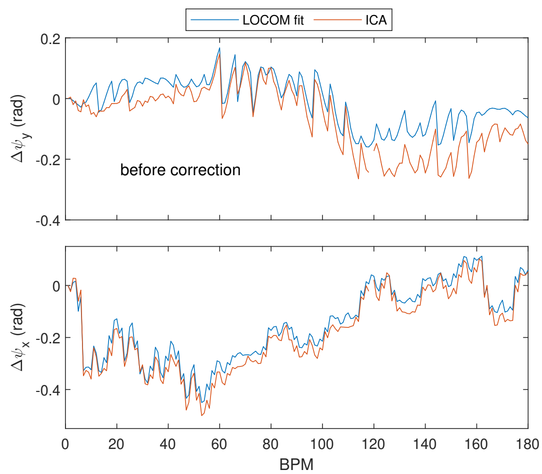

Figure 3: Betatron phase advance differences with the design lattice, obtained by fitting LOCOM data or from TbT BPM data with ICA, for the initial lattice with random errors. One BPM is excluded from TbT data as it was malfunctioning.

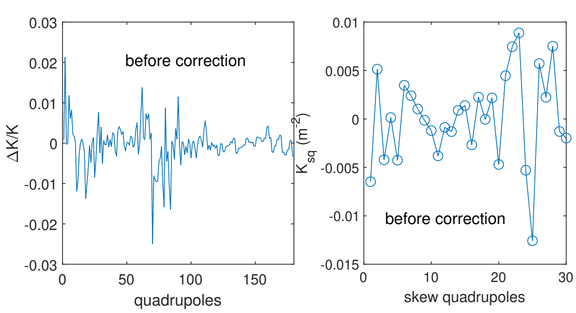

Figure 4: The fitted quadrupole errors, $\frac{\Delta K}{K}$ (left), and skew quadrupole errors (right), for the lattice with initial errors.

Fig. 5). The emittance ratio is 0.012% (see Fig. 7). Figure 6 shows a comparison of phase advance errors at the BPMs after the second correction obtained with LOCOM fitting or with ICA. Note the phase advance errors are substantially lower than the initial errors found in Fig. 3.

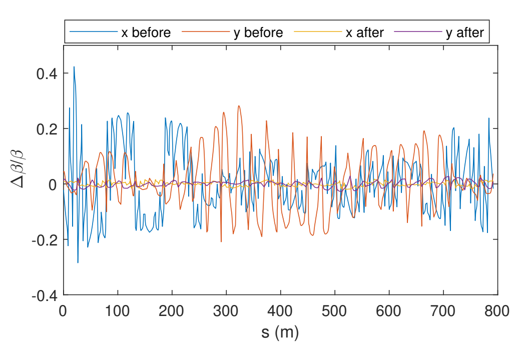

Figure 5: Beta beating from fitted lattices (w/ LOCOM data), before and after correction.

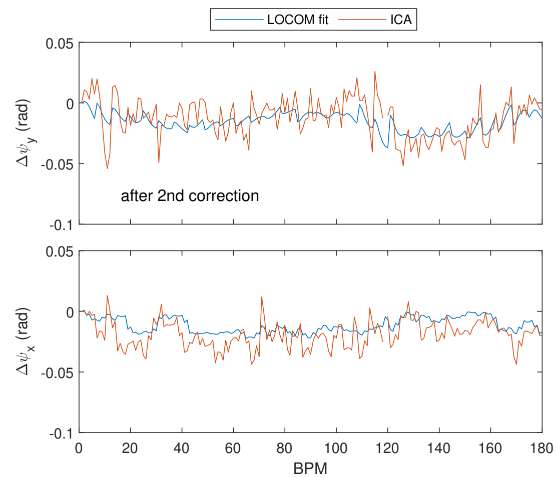

Figure 6: Betatron phase advance differences with the design lattice, obtained by fitting LOCOM data or from TbT BPM data with ICA, after the second correction.

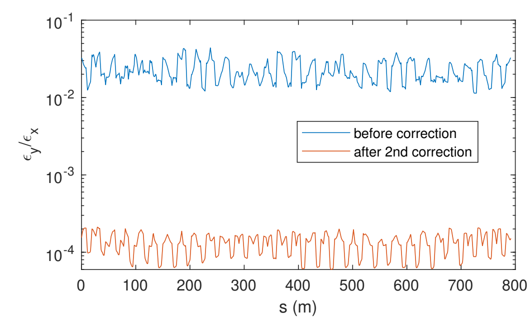

Figure 7: The emittance ratio for the fitted lattices, before and after correction.

The cross-plane orbit modulation can be seen as a model independent measure of the degree of linear coupling in the lattice. After the second correction, the mean x-to-y (y orbit due to horizontal corrector) amplitude is 1.6 µm and the mean y-to-x amplitude is 2.1 µm, down from the values before correction, 5.9 µm and 8.4 µm, respectively. The mean cross-plane mode amplitude ratios in TbT BPM data as defined in Ref. [8] decrease from $r_1 = 0.18$ and $r_2 = 0.27$ to $r_1 = 0.03$ and $r_2 = 0.02$.

SUMMARY

We proposed an improved method to analyze and fit the closed orbit modulation data and to use the results for linear optics and coupling correction. The advantage of the new method is that the number of fitting data points are reduced to 8 per BPM, while the number of total orbit measurements can be substantially increased. We successfully demonstrated the method on the NSLS-II storage ring. The correction results are in good agreement with turn-by-turn BPM data, which serve as an independent verification.

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