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A method for simultaneous linear optics and coupling correction for storage rings with turn-by-turn beam position monitor data

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ABSTRACT

We propose a method to simultaneously correct linear optics errors and linear coupling for storage rings using turn-by-turn (TbT) beam position monitor (BPM) data. The independent component analysis (ICA) method is used to isolate the betatron normal modes from the measured TbT BPM data. The betatron amplitudes and phase advances of the projections of the normal modes on the horizontal and vertical planes are then extracted, which, combined with dispersion measurement, are used to fit the lattice model. The fitting results are used for lattice correction. The method has been successfully demonstrated on the NSLS-II storage ring.

1. Introduction

Linear optics correction has crucial importance in the operation of a storage ring accelerator. There are many error sources that contribute to deviations of the storage ring optics from the ideal model. These include systematic and random errors of quadrupole components of all magnets, feeddown from horizontal orbit offsets in sextupole magnets, and perturbations due to insertion devices. Linear optics errors usually degrade the nonlinear dynamics performance of the storage ring, causing a reduction of dynamic aperture and momentum aperture. Linear optics errors can be corrected with adjustments to the strengths of quadrupole magnets. Correction of linear optics often lead to improvements of injection efficiency and/or Touschek lifetime [1]. It may also be necessary to correct the linear optics in order to deliver certain beam parameters to facilitate user experiments, beam diagnostics, or machine protection. For example, accurate beta functions may be required at certain locations of the ring, or an accurate phase advance may be required between two storage ring components.

Linear coupling between the horizontal and vertical planes and spurious vertical dispersion are other types of common errors in a storage ring that need to be controlled. Linear coupling can be caused by skew quadrupole components of magnets through magnet errors, rolls of quadrupoles, and vertical orbit offset in sextupole magnets. Spurious vertical dispersion can be caused by vertical steering magnets and coupling of the horizontal dispersion through skew quadrupole components in dispersive regions. Both linear coupling and spurious vertical dispersion contribute to the vertical emittance and both can be corrected with skew quadrupoles. The reduction of vertical emittance through linear coupling and spurious vertical dispersion correction is often referred to as "coupling correction".

Linear optics and coupling correction for storage rings is typically done with orbit response matrix based methods (e.g., LOCO (linear optics from closed orbit) [1], used in this paper). By fitting quadrupole and skew quadrupole variables in the lattice model to the measured orbit response matrix and dispersion data, LOCO finds a set of magnet errors that can give rise to the observed lattice errors. Correcting the magnet errors in the machine then leads to improved linear optics and reduced coupling error.

In recent years turn-by-turn (TbT) BPMs have become widely used in storage rings. TbT BPMs not only detect the closed orbit, but also the orbit of a beam in coherent oscillation. From the latter betatron amplitudes and phase advances can be derived [2–4], which in turn can be used for optics correction [4–8]. TbT BPM data also contain linear coupling information and can be used for coupling correction. Methods based on the correction of global and/or local linear coupling resonance driving term were previously proposed or carried out by several authors [9–13]. Typically these methods require linear optics correction beforehand in order to obtain an accurate optics model as needed for coupling correction. Ref. [14] proposed a method that could be used to simultaneously correct linear optics and coupling. One disadvantage of this method is that the BPM errors of the first two BPMs propagate downstream and may affect the fitting results. The extended section by section technique (SBST) developed at LHC can

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be used for optics and coupling correction [15]. The extended SBST method has not been used on storage ring light sources, probably because of its relative complexity as compared to the LOCO method.

In this paper we propose and experimentally demonstrate a new method to simultaneously correct linear optics and coupling. The independent component analysis (ICA) method is first applied to extract the amplitudes and phases of the projection of the normal modes on the horizontal and vertical BPMs [4], which are then compared to their model generated counterparts in fitting. The fitting scheme is similar to LOCO. 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. However, the TbT BPM data based method has a great advantage in that data taking is significantly faster than LOCO. The time for taking orbit response matrix data may vary from 10–100 min for different machines, while TbT BPM data taking takes only a few seconds. Simulation results for our new method were previously reported in Ref. [16].

In the following we first describe the method in Section 2. A discussion of simulation results is in Section 3. Experimental results on the National Synchrotron Light Source-II (NSLS-II) storage ring are presented in Section 4. Conclusion is given in Section 5.

2. Optics and coupling correction with ICA

Betatron motion with linear coupling can be decoupled into two normal modes [17,18]. In general, the beam motion observed by a BPM on any of the two transverse planes has components of both normal modes. Normally the two modes have different betatron tunes and hence can be separated with the ICA method when TbT BPM data from BPMs around the ring are analyzed together [4]. In the ICA process, BPM noise is reduced and other components of beam motion, such as synchrotron motion and nonlinear resonance terms, are isolated from the betatron motion. Therefore, the resulting betatron components have high accuracy.

Each betatron normal mode corresponds to two orthogonal ICA modes. The betatron components on each BPM consist of four ICA modes, which can be expressed as

$$\begin{aligned} x_n &= A\cos\Psi_{1n} - B\sin\Psi_{1n} + c\cos\Psi_{2n} - d\sin\Psi_{2n}, \\ y_n &= a\cos\Psi_{1n} - b\sin\Psi_{1n} + C\cos\Psi_{2n} - D\sin\Psi_{2n}, \end{aligned} \tag{1}$$

where x_n and y_n are observed beam positions on the horizontal and vertical planes at the nth turn, respectively, $\Psi_{1n,2n} = 2\pi\nu_{1,2}n + \psi_{1,2}$, and $\nu_{1,2}$ and $\psi_{1,2}$ are the tunes and initial phases of the normal modes. The initial phases $\psi_{1,2}$ are equal for all BPMs. Typically in a storage ring the linear coupling is weak, in which case the observed x-motion is dominated by one normal mode and the y-motion by the other. For each transverse plane we call the dominant mode the primary mode and the other mode the secondary mode. The tunes of the primary modes are close to the uncoupled tunes for the corresponding planes. For the convenience of discussion, we refer the horizontal primary mode as normal mode 1 and the vertical primary mode as normal mode 2.

The linear coupled motion of betatron coordinates $X = (x, x', y, y')^T$ at any location of the ring can be predicted with the one-turn transfer matrix $\mathbf{T}$. Diagonalizing the transfer matrix, one can relate betatron coordinates to normal mode coordinates

$$\mathbf{\Theta} = \begin{pmatrix} \sqrt{2J_1}\cos\Phi_1 \\ -\sqrt{2J_1}\sin\Phi_1 \\ \sqrt{2J_2}\cos\Phi_2 \\ -\sqrt{2J_2}\sin\Phi_2 \end{pmatrix} \tag{2}$$

via a transformation $\mathbf{X} = \mathbf{P\Theta}$, where $J_{1,2}$ and $\Phi_{1,2}$ are the action and phase variables for the two normal modes, respectively [19]. In particular, the position coordinates x and y are given by

$$\begin{aligned} x &= p_{11}\sqrt{2J_1}\cos\Phi_1 + \sqrt{2J_2}\,(p_{13}\cos\Phi_2 - p_{14}\sin\Phi_2), \\ y &= \sqrt{2J_1}\,(p_{31}\cos\Phi_1 - p_{32}\sin\Phi_1) + p_{33}\sqrt{2J_2}\cos\Phi_2, \end{aligned} \tag{3}$$

where the p_{ij} coefficients are elements of matrix $\mathbf{P}$ and by choice of the initial values of phase variables $\Phi_{1,2}$, we have $p_{12} = p_{34} = 0$ [19]. Not considering damping of the coherent motion (e.g., due to decoherence), the action variables are constants of motion. The phase variables $\Phi_{1,2}$ advances from one location to another and the phase advances for a full turn are $2\pi\nu_{1,2}$.

Clearly the measured beam motion in Eq. (1) and the model predicted motion in Eq. (3) represent the same physical process and are separated in the same form. The amplitudes and phase advances of the two normal modes on the two transverse planes in the two equations should be equal. Equating the amplitudes, we obtain

$$\sqrt{A^2 + B^2} = \sqrt{2J_1}\,p_{11}, \tag{4}$$

$$\sqrt{c^2 + d^2} = \sqrt{2J_2}\,\sqrt{p_{13}^2 + p_{14}^2}, \tag{5}$$

$$\sqrt{C^2 + D^2} = \sqrt{2J_2}\,p_{33}, \tag{6}$$

$$\sqrt{a^2 + b^2} = \sqrt{2J_1}\,\sqrt{p_{31}^2 + p_{32}^2}. \tag{7}$$

The $J_{1,2}$ constants can be calculated by averaging the values derived from the amplitudes of the primary modes, i.e., using Eqs. (4) and (6). Aside from constant initial phase, the phase advances can also be equated, leading to

$$\tan^{-1}\frac{B}{A} = \mathrm{Mod}_{2\pi}(\Phi_1), \tag{8}$$

$$\tan^{-1}\frac{d}{c} = \mathrm{Mod}_{2\pi}\left(\Phi_2 + \tan^{-1}\frac{p_{14}}{p_{13}}\right), \tag{9}$$

$$\tan^{-1}\frac{b}{a} = \mathrm{Mod}_{2\pi}\left(\Phi_1 + \tan^{-1}\frac{p_{32}}{p_{31}}\right), \tag{10}$$

$$\tan^{-1}\frac{D}{C} = \mathrm{Mod}_{2\pi}(\Phi_2), \tag{11}$$

where $\mathrm{Mod}_{2\pi}$ indicates taking modulus of 2π and we have made use of the fact that the value of arctangent can be uniquely determined within $[0, 2\pi)$ when both sine and cosine of an angle is known.

The phase advances of the normal modes $\Phi_{1,2}$ at the BPMs can be calculated with the lattice model. The $\mathbf{P}$ matrix can be computed from the one-turn transfer matrix at the BPM with the numeric procedure given in Ref. [19] or alternatively with equation