SIMULATION AND ANALYSIS OF THE BEAM SIGNAL IN TAIWAN PHOTON SOURCE BOOSTER

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Abstract

We develop data analysis tools for the beam commissioning of the TPS booster. The MIA (Model Independent Analysis) [1, 2] and ICA (Independent Component Analysis) [3, 4] are used to reconstruct the lattice function and beam parameters from turn-by-turn BPM (Beam Position Monitor) data. The BPM data is simulated with the program TRACY [5] for the constant beam energy and acceleration modes. Data analysis includes effects of eddy current, multipole field errors and BPM noises in our simulation.

INTRODUCTION

The TPS (Taiwan Photon Source) [6] booster is a combined function FODO lattice with six superperiods, the total circumference is 496.8 m. To prepare the commissioning of the booster accelerator, we simulate turn-by-turn BPM data to test methods of accelerator model reconstruction and optimize the machine performace. Both MIA and ICA are applied to analyze a massive BPM data by untangling eigenmodes into spatial and temporal wave functions. The ultimate goal of data analysis is to uncover independent source signals.

The MIA or PCA (Principle Component Analysis) [3], tries to uncover the maximum amount of uncorrelated components in a linear transformation of data samples. If eigenmodes are coupled, one needs to apply narrowband filtering to isolate relevant modes [2]. The ICA uses PCA as preprocesor, and carries out un-equal time auto-correlation in order to separate mixed modes [3].

PCA (MIA) had been successfully applied to analyze SLAC PEP-II collider and ICA to the Fermilab booster. We would like to use them for machine analysis at NSRRC starting from the TPS booster synchrotron. The advantage of both methods is that we can measure lattice parameters within seconds by using turn-by-turn BPM data. They are useful for future TPS commissioning, modelling and optimization.

BASIC ALGORITHMS

The BPM data contains information for betatron motion, synchrotron motion (coupled through dispersion), eddy current effects, multipole field errors, noises, etc. Equation 1 shows the horizontal transverse motion as a function of longitudinal position s and turn number N,

$$\begin{aligned} x(s,N) =& \sqrt{\epsilon}\cdot\sqrt{\beta_x(s)}\cos(\nu_x\phi(s)+\chi)\cdot\cos(2\pi\nu_x\cdot N) \\ &+ (\Delta p/p)\cdot D_x(s)\cdot\sin(2\pi\nu_s\cdot N) \\ &+ \text{eddy current effects} \\ &+ \text{multipole field errors} + \text{noises}\,, \end{aligned} \tag{1}$$

where ϵ, β_x, ν_x, ϕ, χ, D_x and ν_s are emittance, beta function, betatron tune, phase advance, phase shift, dispersion and synchrotron tune, respectively. The turn-by-turn data matrix taken by M BPMs for N turns is represented as Eq. 2:

$$X = \begin{pmatrix} x_1(1) & x_1(2) & \cdots & x_1(N) \\ x_2(1) & x_2(2) & \cdots & x_2(N) \\ \vdots & \vdots & \ddots & \vdots \\ x_M(1) & x_M(2) & \cdots & x_M(N) \end{pmatrix}, \tag{2}$$

We compute the covariance matrix and decomposed it with SVD (Singular Value Decomposition) as shown in Eq. 3:

$$C_X = XX^T = U\Lambda U^T,\ \text{where}\ \Lambda = \begin{pmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_M \end{pmatrix}, \tag{3}$$

Λ is a diagonal matrix and the magnitude of diagonal elements are roughly proportional to that of the terms in Eq. 1. One can select a cutoff threshold λ_c, where $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_c \geq \cdots \geq \lambda_M$, to remove the singularity or less important eigenmodes beyond λ_c, i.e., $\lambda_{c+1}\cdots\lambda_M$.

Since the turn-by-turn BPM data can be considered as a linear superposition of source signals in spatial and temporal representations, the SVD of matrix allows us to reconstruct the basic linear particle motion like betatron and synchrotron motions for off-momentum particle ($\Delta p/p \neq 0$). As we show in Eq. 4, the three of largest eigenmodes corresponding to the spatial and temporal vectors are $A_{1,2,3}$ and

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$S_{1,2,3}$:

$$X = (U\Lambda^{1/2})(\Lambda^{-1/2}U^T X) = \begin{pmatrix} A_1 & A_2 & A_3 & \cdots \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ \vdots \end{pmatrix},$$

$$A_1 = \begin{pmatrix} \lambda_1 \sqrt{\beta_{x1}} \sin(\nu_x \phi_1) \\ \lambda_1 \sqrt{\beta_{x2}} \sin(\nu_x \phi_2) \\ \vdots \\ \lambda_1 \sqrt{\beta_{xM}} \sin(\nu_x \phi_M) \end{pmatrix},$$

$$A_2 = \begin{pmatrix} \lambda_2 \sqrt{\beta_{x1}} \cos(\nu_x \phi_1) \\ \lambda_2 \sqrt{\beta_{x2}} \cos(\nu_x \phi_2) \\ \vdots \\ \lambda_2 \sqrt{\beta_{xM}} \cos(\nu_x \phi_M) \end{pmatrix}, \; A_3 = \begin{pmatrix} \lambda_3 D_{x1} \\ \lambda_3 D_{x2} \\ \vdots \\ \lambda_3 D_{xM} \end{pmatrix},$$

$$\begin{aligned} S_1 &= \begin{pmatrix} \cos(2\pi\nu_x \cdot 1) & \cos(2\pi\nu_x \cdot 2) & \cdots & \cos(2\pi\nu_x \cdot N) \end{pmatrix}, \\ S_2 &= \begin{pmatrix} \sin(2\pi\nu_x \cdot 1) & \sin(2\pi\nu_x \cdot 2) & \cdots & \sin(2\pi\nu_x \cdot N) \end{pmatrix}, \\ S_3 &= \begin{pmatrix} \sin(2\pi\nu_s \cdot 1) & \sin(2\pi\nu_s \cdot 2) & \cdots & \sin(2\pi\nu_s \cdot N) \end{pmatrix}, \end{aligned} \tag{4}$$

where $\lambda_1 \simeq \lambda_2 > \lambda_3$. We obtain the β_x, ϕ and ν_x by calculating $\beta_x = (A_1^2 + A_2^2) \times \text{const.}$, $\phi = \tan^{-1}(A_1/A_2)$, $\nu_x = \text{FFT}(S_{1,2})$ and $\nu_s = \text{FFT}(S_3)$, where FFT is fast Fourier transform. The ICA algorithm further considers matrices of time-lag data which are defined as X_τ:

$$X_\tau = \begin{pmatrix} x_1(1+\tau) & x_1(2+\tau) & \cdots & x_1(N+\tau) \\ x_2(1+\tau) & x_2(2+\tau) & \cdots & x_2(N+\tau) \\ \vdots & \vdots & \ddots & \vdots \\ x_M(1+\tau) & x_M(2+\tau) & \cdots & x_M(N+\tau) \end{pmatrix}, \tag{5}$$

for $\tau = 1, 2, 3, \cdots$. One can calculate the unequal time covariance matrix with Eq. 2, $C_X(\tau) \equiv X X_\tau^T$, form symmetric matrices $\overline{C}_X(\tau) = (C_X(\tau) + C_X^T(\tau))/2$, and try to find a unitary matrix $\mathbf{W}$ which diagonalizes all matrices $\overline{C}_X(\tau)$, i.e., $\overline{C}_X(\tau) = \mathbf{W}\mathbf{D}\mathbf{W}^T$, where $\mathbf{D}$ is diagonal. There are several ways to find an approximation of joint diagonalization $\mathbf{W}$. One of them is the extension of Jacobi technique [7]. The ICA modifies the signal extraction on the first line of Eq. 4 as $X = (U\Lambda^{1/2})(\Lambda^{-1/2}U^T X) = (U\Lambda^{1/2}\mathbf{W})(\mathbf{W}^T\Lambda^{-1/2}U^T X)$, the spatial and temporal vectors become $A_{1,2,3} \rightarrow A_{1,2,3}\mathbf{W}$ and $S_{1,2,3} \rightarrow \mathbf{W}^T S_{1,2,3}$. The unitary matrix $\mathbf{W}$ can decouple eigenmodes and thus for eigenvectors once we encounter the coupling problems in PCA (MIA).

SIMULATION STUDIES

We simulate the turn-by-turn BPM data of TPS booster with the program TRACY. Both DC and AC modes are considered in tracking simulation in order to understand the effectiveness of PCA and ICA. For the DC mode, the beam energy and RF voltage are set to constant in tracking simulation. For the AC mode, the repetition rate of TPS booster is 3 Hz. It takes about a hundred thousand turns to accelerate the electron beam from 0.15 to 3.0 GeV.

Sextuple magnets are used to correct the chromaticity induced by eddy currents [8] during the energy ramping. We also include the multipole field errors in simulations. The data of multipole field errors are provided by magnet group. One of the random machines is used for tracking simulation based on the above data. The results of simulated 6-D phase space at one BPM are shown in Fig.'s 1(a), (b) and (c). There are 60 BPMs in TPS booster. We track the particle for 100,660 turns for one ramping cycle.

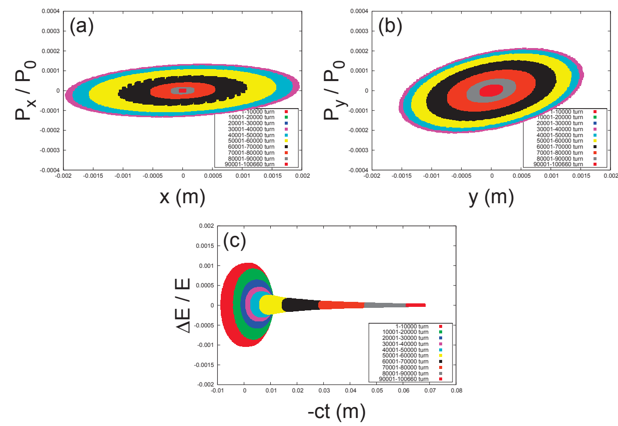

Figure 1: For a ramping cycle in TPS booster, the 6-D phase space, P_x/P_0 vs. x, P_y/P_0 vs. y and $\Delta E/E$ vs. $-ct$ at one of BPMs are shown in (a), (b) and (c), respectively. In these figures, each colour represents a time interval of ten thousand turns.

To measure the machine property, we divide a ramping cycle into ten intervals and collect data for a thousand turns from each interval to extract lattice parameters with PCA or ICA. The noise level of turn-by-turn BPM is expected to be in the range $10 \sim 100$ μm for TPS booster. We assume the noise has a Gaussian distribution with zero mean and $1\sigma = 100$ μm, and assume no gain or roll errors for BPM.

Figure 2 shows an example of measurement results for linear lattice parameters including beta function, dispersion, betatron and synchrotron tunes. The algorithms used to reconstruct beam parameters are given in Eq.'s $2 \sim 4$. The errors of reconstructed values are $< 2\%$ for β_x, $< 3\%$ for β_y, $\sim 3\%$ for horizontal dispersion D_x, and $< 1\%$ for betatron and synchrotron tunes ν_x, ν_y and ν_s. The betatron motion and dispersion terms are gradually decreased due to adiabatic and radiation damping and finally below the BPM noise level. It would be difficult to obtain lattice parameters near the end of a ramping cycle. We can apply a noise excitation to solve this problem.

DISCUSSIONS

We found that both PCA (MIA) and ICA can be used to determine the linear lattice parameters with good precisions. In the near future, we will include beta beat, alignment errors, transverse coupling, wake field, power supply ripple effects, etc. in our simulated BPM data. We will study the effectiveness of PCA and ICA on identifying independent modes.

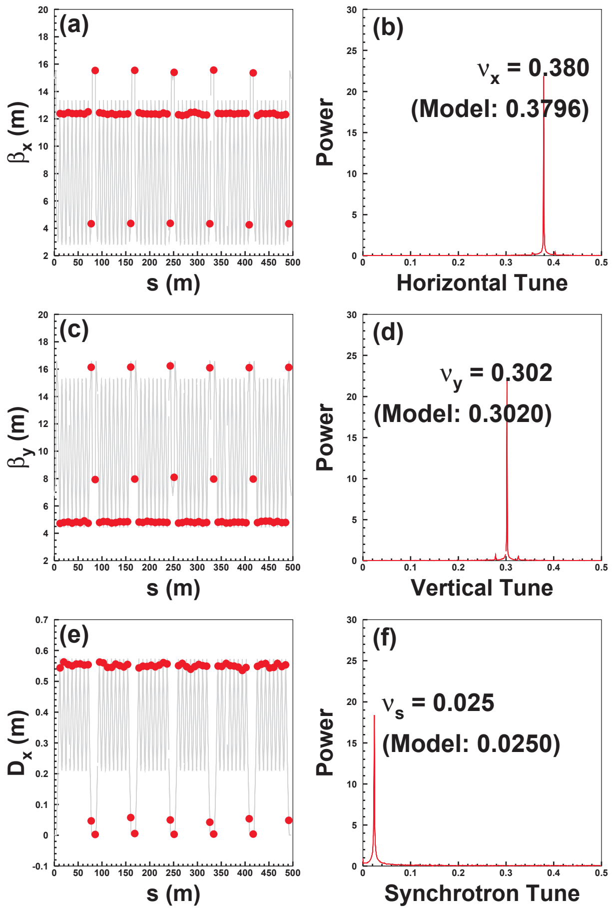

Figure 2: The reconstructed values of β_x, β_y and horizontal dispersion D_x at BPMs are shown as red dots in (a), (c) and (e), respectively. The gray lines are model values along the TPS booster. The reconstructed tunes for ν_x, ν_y and ν_s are shown in (b), (d) and (f), respectively.

The calibration of BPM is crucial for data analysis. The calibration methods of BPM are described in [9]. The BPM noise would be large for measurement of low bunch current in booster. These effects would limit our ability to analyze high order eigenmodes like nonlinear sextupole strength terms [4]. The corrections of BPM alignment errors are also important. The gain and roll of a BPM may introduce additional signals to horizontal and vertical betatron amplitudes and affect betatron coupling measurements [2, 10].

The purpose of analysis is to create a lattice model which is close to real machine. We propose the following procedures for TPS commissioning:

- Establish the lattice model which include multipole field errors and fringe fields based on magnet measurements.
- Identify bad BPMs if any and exclude them from data analysis.
- Calibrate BPMs and find their gain or roll errors.
- Apply ICA to identify and decouple the eigenmodes.
- Identify close orbit distortions, apply orbit corrections and include them in the model.
- Identify betatron couplings and include them in the model.
- Establish a precise linear lattice model, then try to analyze and optimize the nonlinear lattice properties.

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