Beam Position Monitor Troubleshooting Using Principal Component Analysis at the Shanghai Synchrotron Radiation Facility (Postprint)

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Abstract

Beam position monitors (BPMs) have been widely used in all kinds of measurement systems, feedback systems and other areas in particle accelerator field these days. The malfunction of a single BPM can cause serious consequences such as the failure of the orbit feedback and the transverse feedback. A troubleshooting has been made to prevent the defective BPMs from affecting the accuracy and stability of the storage ring in Shanghai Synchrotron Radiation Facility (SSRF). Different types of malfunctions have been successfully identified by using the idea of principal component analysis (PCA).

Full Text

Preamble

Beam Position Monitor Troubleshooting by Using Principal Component Analysis in Shanghai Synchrotron Radiation Facility

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Abstract: Beam position monitors (BPMs) have been widely used in measurement systems, feedback systems, and other areas throughout the particle accelerator field. The malfunction of a single BPM can cause serious consequences such as the failure of orbit feedback and transverse feedback systems. A troubleshooting methodology has been developed to prevent defective BPMs from affecting the accuracy and stability of the storage ring at the Shanghai Synchrotron Radiation Facility (SSRF). Different types of malfunctions have been successfully identified using principal component analysis (PCA).

Keywords: Singular value decomposition, Principal component analysis, Beam position monitors, SSRF
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Introduction

A. Various Defective BPMs in SSRF

A beam position monitor (BPM) system is an essential diagnostic tool in the storage ring of a light source. The SSRF storage ring is equipped with 140 BPMs located across 20 cells to monitor beam dynamics [**?**]. The BPMs positioned after insertion devices (IDs) or bending magnets are particularly important because they also serve as the orbit feedback system to ensure electron beam stability. BPMs with low resolution must be excluded from the feedback system to maintain high beam stability. Correlation analysis based on principal component analysis (PCA) is used to disqualify BPMs that exhibit low confidence or are considered faulty or noisy. The confidence levels of BPMs included in the feedback system can also be used to estimate beam dynamics stability. Some BPMs can be used for measurements beyond beam position, such as relative beam current or lifetime. Therefore, any abnormal BPM must be identified and addressed.

A typical BPM system consists of a probe (button-type or stripline-type), electronics (Libra Electronics/Brilliance in SSRF), and signal transmission components (cables and related hardware). Since SSRF commissioning began in 2009, the following causes of BPM noise have been identified: (1) permanent damage to individual probes or corresponding cables, (2) misaligned probes (position/angle), (3) high-frequency vibrations, (4) electronics noise, and (5) other miscellaneous factors.

A damaged probe or cable renders the BPM signals completely useless, and such BPMs should be ignored until replacement or repair. Probe misalignment causes gain shifts that require recalibration. Vibration and electronics noise can also degrade BPM performance. PCA has proven to be an efficient and sufficient tool for locating BPM malfunctions at SSRF.

B. PCA Methodology

PCA is a useful statistical technique for identifying interesting patterns within massive datasets across various fields. It was introduced to the particle accelerator community as a major constituent of model-independent analysis (MIA) theory by Irwin J and Wang C X in Dr. Wang' s doctoral work [?]. A series of studies inspired by MIA have since been conducted, including optical parameter measurements [?, ?, ?, ?, ?] and performance estimation [?, ?]. The correlated BPM data matrix is regarded as a linear combination of different physical modes at different locations, enabling statistical analysis of beam dynamics without knowledge of the accelerator lattice model.

Assuming the BPM output signals take the following form:

$$b_i(t) = a^i_j m_j(t)$$

where $b_i(t)$ is the signal from the ith BPM, $m_j(t)$ is the jth physical mode, and a^i_j is the coefficient of the jth mode. The Einstein summation convention is adopted here to simplify the expression.

The following physical modes are shared by all BPMs in SSRF:

1) A major contribution to beam dynamics comes from betatron oscillation. This has two degrees of freedom, so two physical modes should be sufficient to describe it: $m_1(t) = \sin(\omega t + \phi_0)$ and $m_2(t) = \cos(\omega t + \phi_0)$, where ϕ_0 is a trivial initial phase shared by all BPMs. The corresponding coefficients a^i_1 and a^i_2 in Eq. (1) relate to the β function and should be identical or at least relatively close to each other.
2) Energy oscillation is also visible.
3) Global signals are occasionally observed from RF systems, power supplies, and other parts of SSRF.

Generally, variables from physical phenomena caused by different mechanisms are considered independent, and independent variables are always linearly uncorrelated. Thus, the m_j modes form an orthogonal basis that can fully describe beam dynamics in its vector space. PCA serves as a tool to find this basis. Using singular value decomposition (SVD), the BPM matrix B can be decomposed into three matrices [?]:

$$B_{m\times n} = U_{m\times m} S_{m\times n} V^\dagger_{n\times n}$$

where U and V are unitary square matrices and S is a diagonal matrix. In MIA, U is called the temporal matrix, V the spatial matrix, and S the singular value matrix for the following reasons: - U is the matrix of eigenvectors of the covariance matrix $BB^\dagger$, and each column of U corresponds to the time series waveform of a specified mode; - V is the matrix of eigenvectors of the covariance matrix $B^\dagger B$, and each column of $V^\dagger$ corresponds to the spatial distribution of a specified mode; - Each element of S is nonnegative and real, corresponding to the variance of a specified mode.

The decomposition can be expanded more visually as:

$$b_{ij} = \sum_k s_k u_{ik} v_{kj}$$

where b, s, u, and v are elements of matrices B, S, U, and $V^\dagger$, respectively. Eq. (3) implies that, since independence is a stronger form of linear independence, the BPM data consist of a complete basis corresponding to the independent physical modes suggested by PCA. Thus, Eq. (3) can be further expanded as:

$$b_{ij} = s_{\beta,1} u^i_{\beta,1} v^j_{\beta,1} + s_{\beta,2} u^i_{\beta,2} v^j_{\beta,2} + s_\eta \eta^i v^j_\eta + s_{EN} EN^i v^j_{EN} + s_N N^i v^j_N$$

where β denotes the two modes of betatron oscillation, η denotes energy oscillation, EN denotes electronics noise, and N denotes all other noise. By examining the eigenvectors and singular values, different modes can be further analyzed.

II. Extracted Modes from SSRF Data

A. Betatron Oscillation

The betatron oscillation is usually suppressed by the transverse feedback system and may not be particularly significant. To evaluate the relationship between BPM signals and the calculation model, a kicker was used in an experiment on November 1, 2010, to induce transverse oscillation. Two components with almost identical singular values were extracted, and one component is shown in Fig. 1(a). Fig. 1(b) shows the corresponding spectrum of this component, indicating that it represents betatron oscillation at the frequency of the horizontal tune. The other component had the same characteristics except for a $\pi/2$ phase shift. These two components form a complete basis in the betatron oscillation vector space, and the β function can be derived using the spatial vectors.

By comparing measured and calculated β functions, BPMs that did not work properly can be identified (Fig. 2(a)). Moreover, the relative difference for each BPM (Fig. 2(b)) can be used to create a list of BPM confidence levels. BPM No. 68 is a reference BPM. With a single button probe serving as four identical input channels, BPM No. 68 theoretically does not contain beam dynamics information. As shown in Fig. 2, BPM No. 68 does not reflect betatron oscillation behavior.

B. Energy Oscillation

Another beam dynamics mode extracted by PCA is energy oscillation. This mode has lower frequency, and its oscillation phase tends to be invariant. In other words, the mode exhibits the same behavior for all BPMs within one resonance period. Thus, this "location-free" component is one-dimensional in the vector space. A typical waveform of energy oscillation recorded on July 22, 2010, is shown in Fig. 3(a). The spectrum in Fig. 3(b) confirms that the mode is limited to the low-frequency region.

Following the procedures in Sec. II and comparing calculated and measured dispersion functions, we found that malfunctions corresponded to the spatial vector of this component (Fig. 4).

C. Noise

After SVD, the modes were separated. Let us examine, for example, the mode corresponding to the 9th singular value (referred to as the 9th mode) from the data recorded on April 27, 2011. The waveform in Fig. 5(a) does not appear particularly revealing, but the spectrum in Fig. 5(b) demonstrates the mode' s characteristics: it is a combined signal of horizontal betatron oscillation and approximately 29 kHz electronics noise, with vertical betatron oscillation coupled into the mode as well. The spatial distribution of the mode provides weights for all BPMs. Fig. 6 gives a rough list of BPMs suffering from this type of noise, which are not suitable for extremely precise measurements. Note that although BPM No. 68 is completely unrelated to the beam and provides only false signals, it shows relatively stable electronics.

III. Using PCA in BPM Troubleshooting

The BPM malfunctions mentioned in Sec. I behave differently in PCA. Permanent damage to a cable or probe causes a total mismatch between measured physical parameters and theoretical data. Probe misalignment causes shifted parameter measurement results, but these are still adjustable. However, vibration or electronics noise may introduce new modes that are shared by some BPMs.

A series of BPM turn-by-turn data matrices were recorded on April 27, 2011, and the results are used here to illustrate BPM troubleshooting. The betatron oscillation was induced using a kicker magnet so that the first two major principal components after BPM matrix decomposition were the betatron oscillation. The third mode was energy oscillation. BPMs suffering from electronics noise (the 9th mode) were previously shown in Figs. 5 and 6.

The β functions and dispersion functions were averaged and compared with the model in the first phase, as shown in Figs. 7(a), 8(a), and 9(a). The relative differences between measured parameters and model values are shown in Figs. 7(b), 8(b), and 9(b) to illustrate BPM fitness.

It is obvious that BPM No. 68 did not share the main beam dynamics, and its corresponding β-functions and dispersion function (the spatial vectors) were all zeros, which did not approximate the mode values.

Histograms of measured horizontal β-functions, vertical β-functions, and energy oscillations were created after a series of measurements (Fig. 10). BPMs with larger variances in these parameters indicate potential mismatches between the RF system and ADC sampling clock or DDC local oscillator in the electronics.

The BPMs shown in Fig. 6 were believed to have serious electronics noise, and this BPM list is not suitable for accurate measurements. The troubled

BPMs shown in Fig. 4(a) were not necessarily useless in general. Those with surprisingly small variances in Fig. 4(b), such as BPM number 123, might suffer from poor electrode configurations, alignments, or cable connections that contributed offsets to the results and were hopefully removable or adjustable.

For unusable BPMs, not only were the extracted Twiss parameters far from designed values, but the measured results were also very unstable (i.e., had very large variances). This was due to rapid changes in the local lattice or serious problems in the detector system. The lattice was presumably stable during normal operations, so these BPMs were marked as damaged for future testing.

All these measurements and statistics were used to construct a list of confidence levels. BPMs with higher confidence levels receive higher priority in critical measurements or feedback systems. Misaligned BPMs would be recalibrated to eliminate gain shifts. Damaged BPMs would be rechecked, and cables would be replaced if other probe components still functioned.

IV. Conclusion

By extracting physical signals from the BPM data matrix, PCA has proven to be a useful tool for separating various malfunctions in BPM systems at SSRF. The machine model can be used to verify probe or cable availability. Measurement histograms can be used to check electronics variances. High-frequency vibration or electronics noise can be identified in other modes. Thus, different defective BPMs exhibit different behaviors and can be categorized accordingly. This approach is promising for troubleshooting procedures and could be optimized for online usage, such as dynamically updating BPM confidence levels.

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Note: Figure translations are in progress. See original paper for figures.