NUCLEAR SCIENCE AND TECHNIQUES **25**, 020102 (2014)

Beam position monitor troubleshooting by using principal component analysis in Shanghai Synchrotron Radiation Facility*

CHEN Zhi-Chu (陈之初),[1,2] LENG Yong-Bin (冷用斌),[1,2,†] YUAN Ren-Xian (袁任贤),[1,2]
YAN Ying-Bing (阎映炳),[1,2] and LAI Long-Wei (赖龙伟)[1,2]

[1] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[2] *Shanghai Synchrotron Radiation Facility, Chinese Academy of Sciences, Shanghai 201204, China*
(Received June 18, 2013; accepted in revised form September 11, 2013; published online March 20, 2014)

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).

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

DOI: 10.13538/j.1001-8042/nst.25.020102

I. INTRODUCTION

A. Various of Defective BPMs in SSRF

A beam position monitor (BPM) system, is an essential diagnostics in storage ring of a light source. The storage ring in SSRF is equipped with 140 BPMs located at 20 cells of the storage ring to monitor the beam dynamics [1]. The BPMs at the beam lines after the insertion devices (ID) or the bending magnets are of great importance, because they also serve as the orbit feedback system to ensure stability of the electron beams. BPMs of low resolution must be excluded from the feedback system for high stability of the beam. Correlation analysis based on principal component analysis (PCA) is used for disqualifying BPMs having low confidence or being considered as faulty or noisy. The BPM confidence levels included in the feedback system can also be used to estimate stability of the beam dynamics. Some BPMs can be used to do measurements other than the beam position, such as the (relative) beam current or life time. Therefore, an abnormal BPM should be found and treated.

A typical BPM system consists of the probe (button-type or stripline-type), electronics (Libra Electronics/ Brilliance in SSRF) and transferring component (cables and such). Ever since the SSRF commissioning in 2009, the following BPM noise-causes have been found: 1) permanently damage to individual probe or corresponding cable, 2) misaligned (position/angle) probes, 3) high-frequency vibrations, 4) electronics noise, and 5) others.

A damaged probe or cable means totally useless of the signals from the BPM, which should be ignored until its replacement or repair. A misalignment causes gain shift of the probe, hence the need of recalibration. The vibration and electronic noise of a BPM result in increase of its measurement variation and uncertainty. PCA has been an efficient and sufficient tool to locate the BPM malfunctions at SSRF.

B. PCA

PCA has been a useful statistical technique for finding interested patterns within mass data in various fields. It was introduced to the society of particle accelerators as a major constituent part of the model-independent analysis (MIA) theory by Irwin J and Wang C X in Dr. Wang's doctoral work [2]. A series of work inspired by MIA have been done since then such as the optical parameters measurement [3–7] and performance estimate [8, 9]. The correlated BPM data matrix is regarded as a linear combination of different physical modes at different locations. A statistical analysis is then applied to study the beam dynamics without knowing the lattice model of accelerator.

Assuming the following form of BPM output signals:

$$b_i(t) = a_i^j m_j(t), \tag{1}$$

where, $b_i(t)$ is signal of the i^{th} BPM, $m_j(t)$ is the j^{th} physical mode and a_i^j is coefficient of the j^{th} mode. The Einstein summation convention is adopted here to simplify the expression.

It is found that the following physical modes are shared by all the BPMs in SSRF:

1) A major contribution to the beam dynamics is the betatron oscillation. It has two degrees of freedom, so two physical modes should be sufficient to determine 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 that is shared by all BPMs. The corresponding coefficients a_i^1 and a_i^2 in Eq. (1) are the β function and should be identical or at least relatively close to each other.

2) The energy oscillation is visible.

* Supported by National Natural Science Foundation of China (No.11075198)
† Corresponding author, lengyongbin@sinap.ac.cn

3) Global signals are occasionally observed from the RFs, the power supplies and other parts of SSRF.

Generally, variables of the physical phenomena caused by different physical mechanisms are considered independent, and independent variables are always linearly uncorrelated. Then, m_j's have formed an orthogonal basis which can fully describe the beam dynamics in its vector space. PCA is tool to find the basis. By using the singular value decomposition (SVD), the BPM matrix $\boldsymbol{B}$ can be decomposed into three matrices [2]:

$$\boldsymbol{B}_{m\times n} = \boldsymbol{U}_{m\times m}\boldsymbol{S}_{m\times n}\boldsymbol{V}^{\dagger}_{n\times n}, \tag{2}$$

where $\boldsymbol{U}$ and $\boldsymbol{V}$ are unitary square matrices and $\boldsymbol{S}$ is a diagonal matrix. In MIA, $\boldsymbol{U}$ is called the temporal matrix, $\boldsymbol{V}$ the spatial matrix and $\boldsymbol{S}$ the singular value matrix for the following reasons:

- $\boldsymbol{U}$ is the matrix of the eigenvectors of the covariance matrix $\boldsymbol{B}\boldsymbol{B}^{\dagger}$ and each column of $\boldsymbol{U}$ corresponds to the time series waveform of a specified mode;
- $\boldsymbol{V}$ is the matrix of the eigenvectors of the covariance matrix $\boldsymbol{B}^{\dagger}\boldsymbol{B}$ and each column of $\boldsymbol{V}^{\dagger}$ corresponds to the spatial distribution of a specified mode;
- Each element of $\boldsymbol{S}$ is nonnegative and real, and it corresponds to the variance of a specified mode.

The decomposition can be expanded in a more visual way:

$$b^i_j = s^k_k u^i_k v^k_j, \tag{3}$$

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

$$\begin{aligned} b^i_j = {}& s^{\beta,1}_{\beta,1}u^i_{\beta,1}v^{\beta,1}_j + s^{\beta,2}_{\beta,2}u^i_{\beta,2}v^{\beta,2}_j + s^{\eta}_{\eta}u^i_{\eta}v^{\eta}_j \\ & + s^{\mathrm{EN}}_{\mathrm{EN}}u^i_{\mathrm{EN}}v^{\mathrm{EN}}_j + s^{\mathrm{N}}_{\mathrm{N}}u^i_{\mathrm{N}}v^{\mathrm{N}}_j, \end{aligned} \tag{4}$$

where, β denotes the two modes of the betatron oscillation, η denotes the energy oscillation, EN denotes the electronics noise and N denotes all other noise. By examining the eigenvectors and the 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 quite significant. To evaluate the relation between the BPM signals and calculation model, a kicker was used in an experiment on November 1, 2010, to invoke the transverse oscillation. Two components of the almost same singular values were extracted and one of the components is shown in Fig. 1(a). Fig. 1(b) shows corresponding spectrum of this component, indicating that it is the betatron oscillation in the frequency of the horizontal tune. The other component had the same characteristics except for a $\pi/2$ phase shift. The two components can form a complete basis in the betatron oscillation vector space, and the β function can be derived by using the spatial vectors.

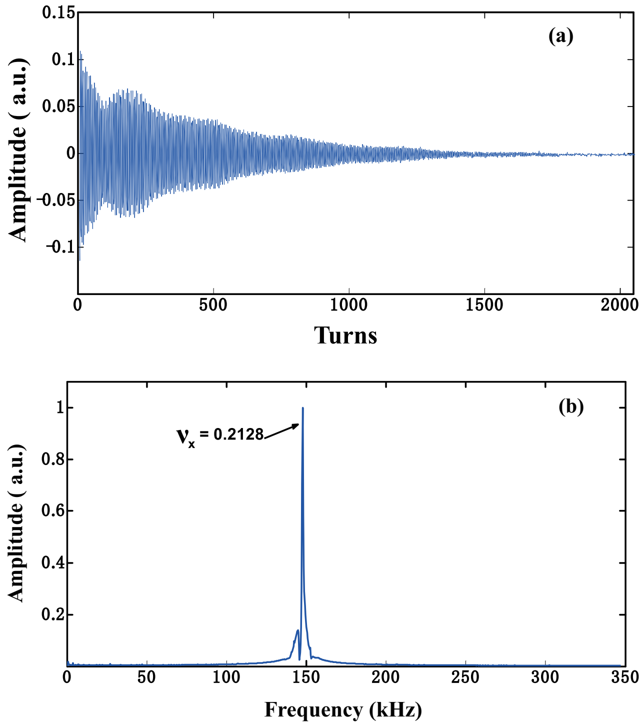

Fig. 1. (Color online) Waveform (a) and spectrum (b) of the betatron oscillation.

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

B. Energy Oscillation

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

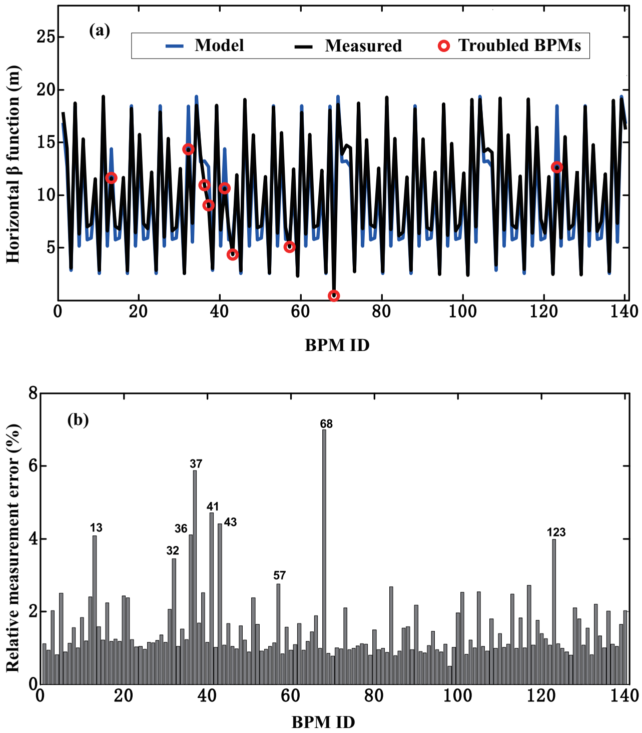

Fig. 2. (Color online) Comparison of the measured and modeled betatron function (a), and the standard deviations (b).

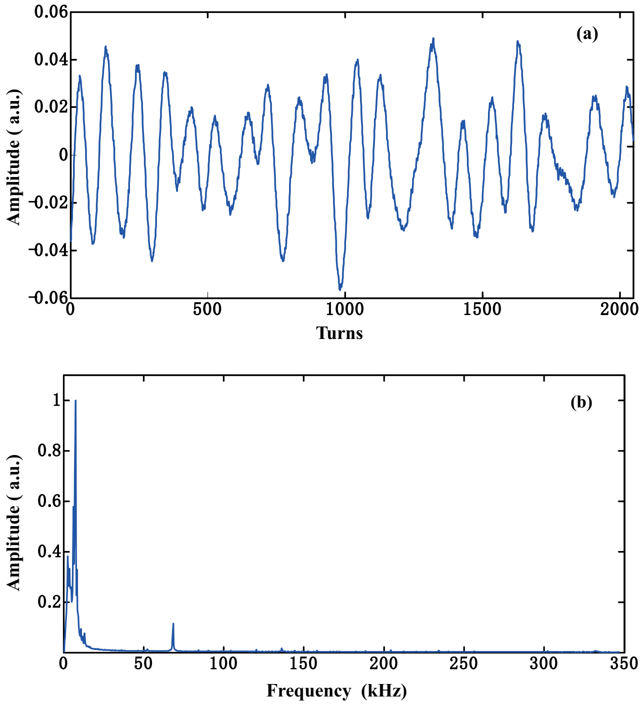

Fig. 3. (Color online) Waveform (a) and spectrum (b) of the energy oscillation.

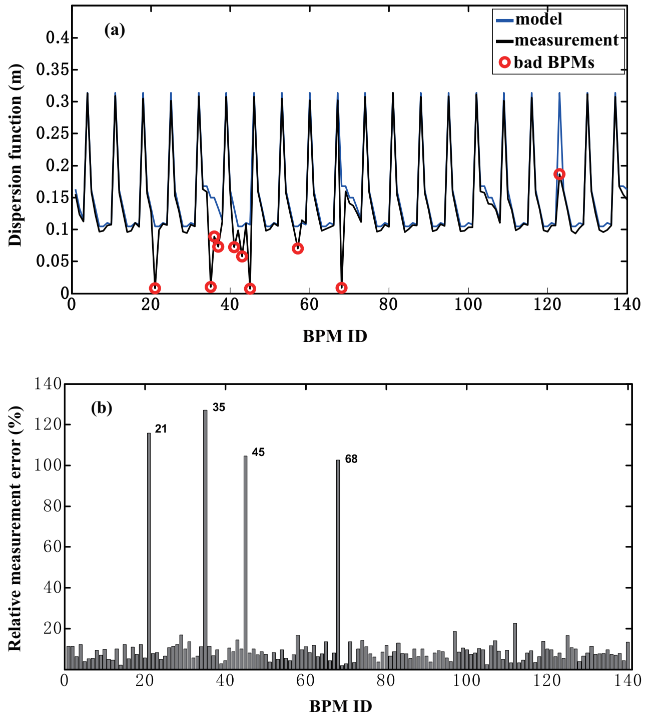

Fig. 4. (Color online) Comparison of the measured and modeled dispersion function (a), and the standard deviations (b).

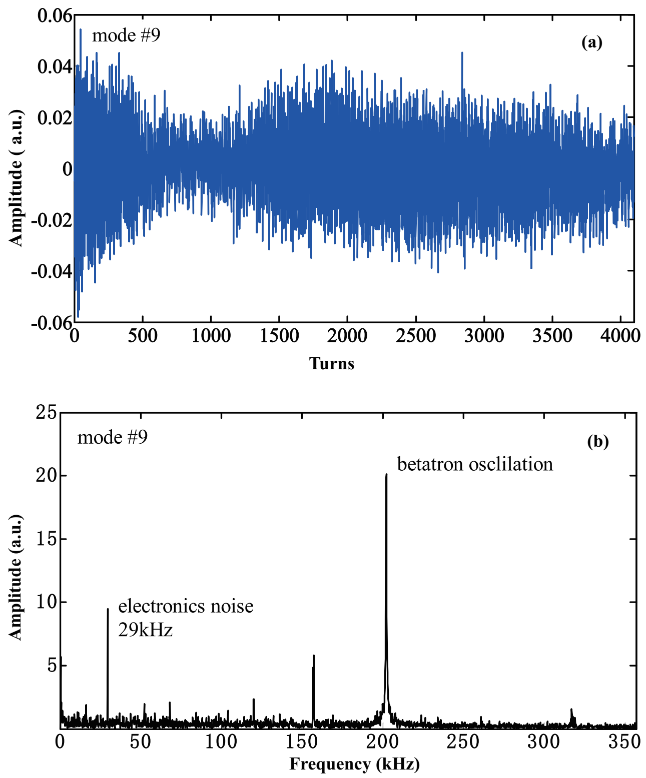

Fig. 5. (Color online) Waveform (a) and spectrum (b) of the 9th mode.

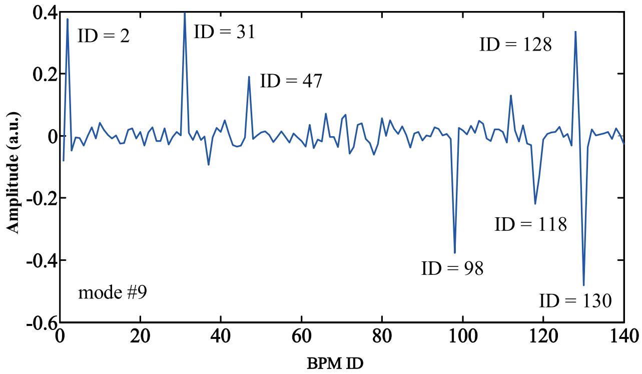

Fig. 6. (color online) Spatial distribution of the 9th mode.

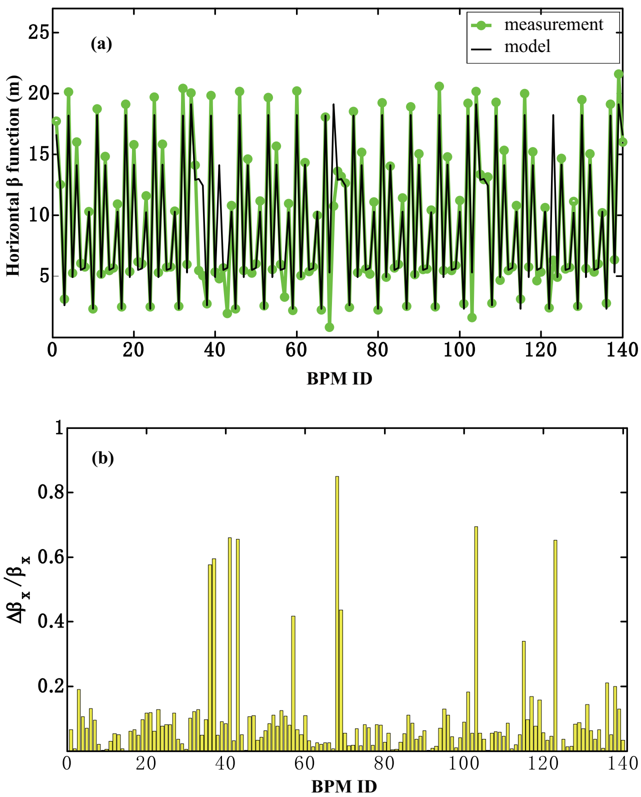

Fig. 7. (Color online) Comparison of the measured and calculated horizontal β-functions (a), and the standard deviations (b).

low frequency area.

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

C. Noise

After an SVD, the modes were separated. Let's take a close look at, for example, the mode corresponding to the 9th singular value (referred as the 9th mode) of the data on April 27,

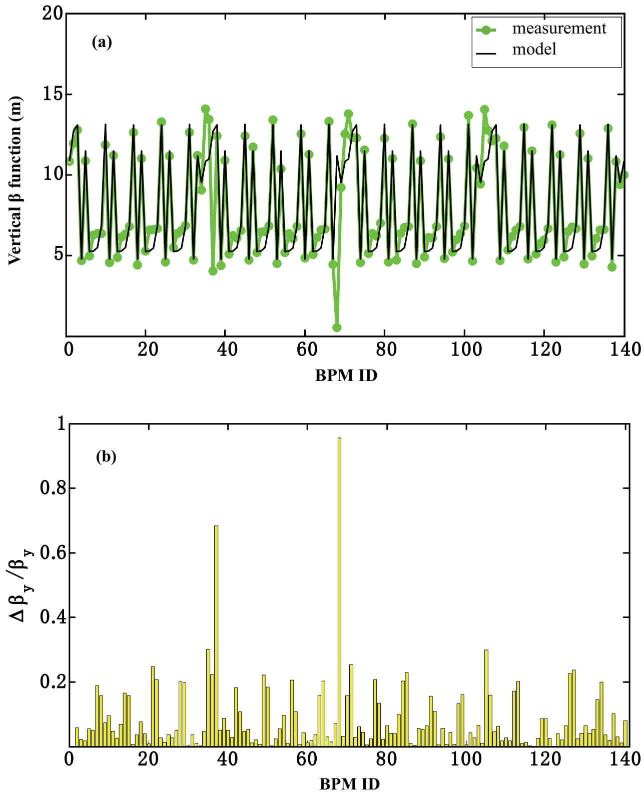

Fig. 8. (Color online) Comparison of the measured and calculated vertical β-function (a), and the standard deviations (b).

2011. The waveform in Fig. 5(a) of the mode does not seem to show much inspiring, but the spectrum in Fig. 5(b) demonstrates characteristics of the mode: it is a combined signal of the horizontal betatron oscillation and some 29 kHz electronics noise, and the vertical betatron oscillation was coupled into the mode as well. The spatial distribution of the mode gives the weights in all the BPMs. Fig. 6 gives a rough list of the BPMs which were suffering from this kind of noise and they are not suitable for extreme precise measurements. One sees that although BPM No. 68 is absolutely not related to the beam and gives only false signals, with its use of a relatively stable electronics.

III. USING PCA IN BPM TROUBLESHOOTING

The BPM malfunctions mentioned in Sec.I do not behave alike in the PCA. Permanent damage to a cable or probe makes a total mismatch of measured physical parameters to their theoretical data. A probe misalignment causes shifted results of parameter measurement, but this is still adjustable. The vibration or electronics noise, however, may introduce some new modes which are shared by some of the BPMs. A series of BPM turn-by-turn data matrices were recorded on April 27, 2011. The results are used here to illustrate the BPM troubleshooting.

The betatron oscillation was invoked by using a kicker

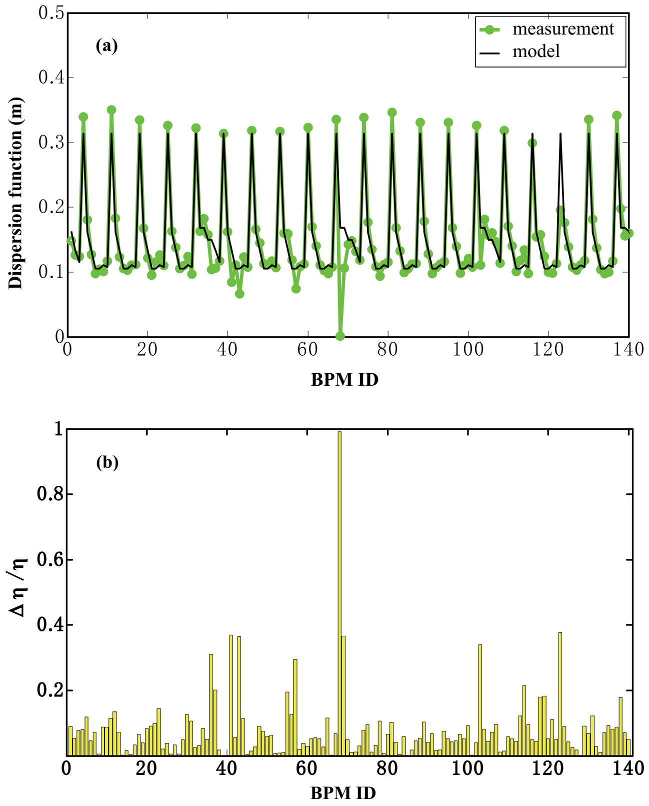

Fig. 9. (Color online) Comparison of the measured and calculated dispersion function (a), and the standard deviations (b).

magnet so that the first two major principal components after the decomposition of the BPM matrix were the betatron oscillation. The third mode was the energy oscillation. The BPMs that were suffering from the electronics noise (the 9$^{\text{th}}$ mode) had already been shown previously in Figs.5 and 6.

The β functions and dispersion functions were averaged, and then compared with the model in the first phase as shown in Figs. 7(a), 8(a) and 9(a). The relative differences between the measured parameters and the model ones are shown in Figs.7(b), 8(b) and 9(b) to illustrate the fitnesses of the BPMs. It is obvious that BPM No. 68 did not share the main beam dynamics and the corresponding β-functions and dispersion function (the spatial vectors) were all zeros which were not approximate to the mode values.

Histograms of the measured horizontal, vertical β-functions and the energy oscillations had been made after a series of measurements (Fig. 10). The BPMs with larger variances of these parameters indicate that there might be a mismatch between the RF and the ADC sampling clock or the DDC local oscillator of the very 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. The ones with surprisingly small variances in Fig. 4(b), e.g., BPM number 123, might due to poor configurations of the electrodes, alignments or cable connections which contributed some offset to the results

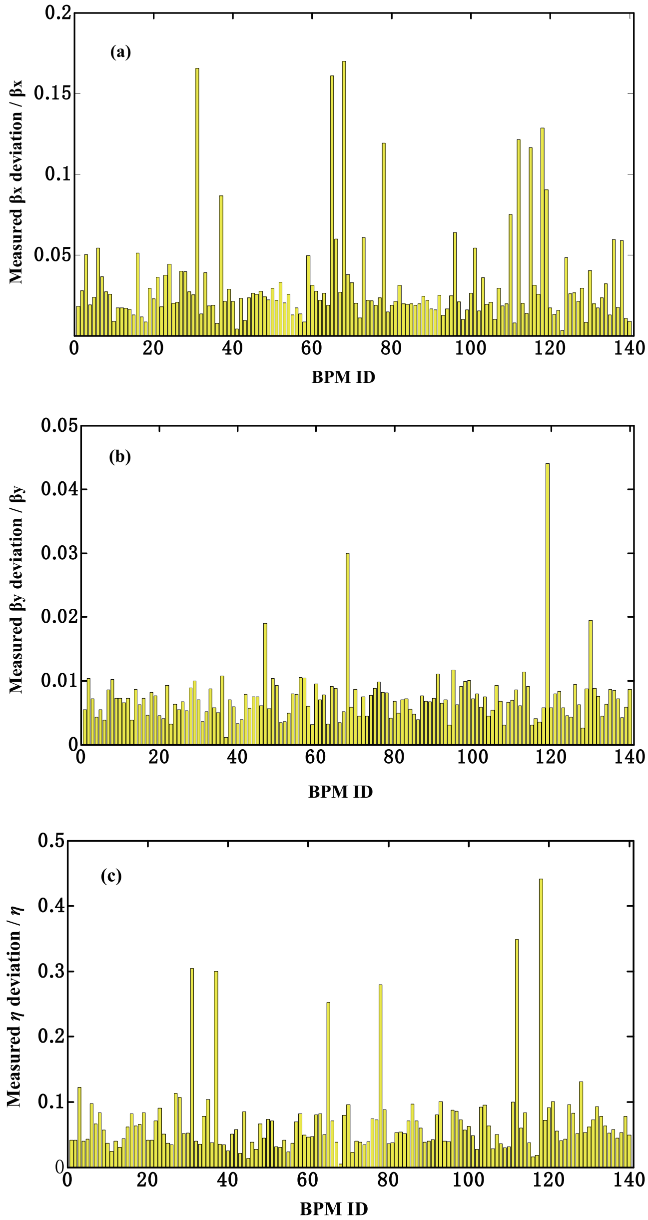

Fig. 10. (Color online) Measurement variances of the horizontal β-function (a), vertical β-function (b) and the dispersion function (c).

and were hopefully removable or adjustable.

For those unusable BPMs, not only the extracted Twiss parameters were not close to the designed ones, but also the measured results were very unstable, i.e., had very large variances. This was due to rapid changes of the local lattice or serious problems of the detector system. The lattice was presumably stable during the normal operations so that these BPMs were marked as damaged for future tests.

All these measurements and statistics had been used to construct a list of confidence levels. The ones with higher confidence levels would be in higher priority in serious measurements or feedbacks. The misaligned ones would be calibrated once more to get rid of the gain shifts. The damaged ones would be rechecked and cables would be replaced if the other parts of the probe would still work.

IV. CONCLUSION

By extracting the physical signals from the BPM data matrix, PCA has been proved to be a useful tool to separate various malfunctions in the BPM systems in SSRF. The machine model can be used to verify the availabilities of the probes or cables. The histogram of the measurements can be used to check the variances of the electronics. The high-frequency vibration or electronics noise can be found in other modes. Thus, different defective BPMs might behave differently and then can be categorized. Being inspiring in the procedure of the troubleshooting, this idea would be optimized for online usage, such as dynamically update the confidence levels of the BPMs.

[1] Leng Y B, Zhou W M, Yuan R X, *et al*. Nucl Tech, 2010, **33**: 401–404.(in Chinese)

[2] Wang C X. Model independent analysis of beam centroid dynamics in accelerators, Stanford Ph.D. Thesis (Stanford University), 1999.

[3] Irwin J, Wang C X, Yan Y T, *et al*. Phys Rev Lett, 1999, **82**: 1684.

[4] Aiba M. Phys Rev Spec Top-AC, 2009, **12**: 081002.

[5] Yan Y T and Cai Y H. Nucl Instrum Methods, 2006, **A558**: 336–339.

[6] Wang C X, Sajaev V, Yao C Y. Phys Rev Spec Top-AC, 2003, **6**: 104001.

[7] Chen Z C, Leng Y B, Yuan R X, *et al*. Nucl Sci Tech, 2013, **24**: 010102.

[8] Calaga R, Tomás R. Phys Rev Spec Top-AC, 2004, **7**: 042801.

[9] Wenninger J, Goddard B, Kain V, *et al*. TPAP017: Beam stability of the LHC beam transfer line TI8, Proceedings of the 2005 particle accelerator conference, Knoxville, Tennessee, USA, May 2005, 1523–1525.