Orbit correction algorithm for SSRF fast orbit feedback system

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Abstract A fast orbit feedback system is designed at SSRF to suppress beam orbit disturbance within sub-micron in the bandwidth up to 100 Hz. The SVD (Singular value decomposition) algorithm is applied to calculate the inverse response matrix in global orbit correction. The number of singular eigenvalues will influence orbit noise suppression and corrector strengths. The method to choose singular eigenvalue rejection threshold is studied in this paper, and the simulation and experiment results are also presented.

Key words Fast orbit feedback system, Singular value decomposition, Shanghai Synchrotron Radiation Facility

1 Introduction

According to the design specifications, beam stability of Shanghai Synchrotron Radiation Facility (SSRF) is $5-23 \mu m$ in horizontal plane and $1-2 \mu m$ in vertical plane^[1]. The fast orbit feedback (FOFB) system of SSRF is implemented to suppress orbit noise within sub-micron in the range of DC to $100 \text{ Hz}^{[2]}$.

The FOFB system consists of 40 BPMs and 60 pairs of correctors. A star topology is used to build an effective transfer system for synchronous data from different VME crates. The SVD algorithm is applied to calculate the inverse response matrix in the fast orbit feedback system.



Fig.1 Layout of the FOFB system. S1–S10, VME SBCs; A, reflective memory; B, interface to BPM electronics; C, interface to power supply controller; D, timing module.

2 Analysis of response matrix

In testing and commissioning of the fast orbit feedback system, 12 eBPMs out of 40, and 20 pairs of correctors out of 60, are chosen. The normal method to measure the response matrix is the least square algorithm, which is accomplished by setting correctors and measuring the beam orbit step by step. Since an orbit drift of several microns was observed in about 1 min in the storage ring of SSRF, the least square algorithm would bring system errors during the calculation of the response matrix. So the direct method to get the orbit difference between two steps of correctors setting was applied to calculate the response matrix. The measured

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response matrix is shown in Fig.2. The BPM index 1-12 is in the horizontal plane, and the BPM index 13-24 is in the vertical plane.

Coupling between horizontal and vertical planes affects the orbit correction, and applying correction in one plane can introduce distortion on the corrected orbit in the other plane^[3]. The measured response matrix indicates that the crosstalk between horizontal and vertical planes is weak, and the average level is below 0.5%. Therefore, in the calculation of the inverse response matrix, the inverse sub-matrices in horizontal and vertical plane were generated respectively, and then the inverse response matrix was formed.

Because of the storage ring lattice and the noise of the BPM system, the nearly singular values were normally generated when implementing SVD algorithm to calculate the inverse response matrix. Consequently, a choice of singular eigenvalue rejection threshold was needed, so that the requirements of correction precision and corrector strengths



Fig.2 The response matrix.



Fig. 3 The inverse response matrix.



Fig.4 Eigenvalues of the response sub-matrix in each plane.

could be satisfied. The inverse response matrix is shown in Fig.3. The eigenvalues of the response sub-matrix in each plane are shown in Fig.4. If there are some nearly singular eigenvalues, the power supplies of correctors are easily overloaded when the fast orbit feedback system is in operation.

3 Analysis of correction errors

Let Δx be the difference between reference orbit and current orbit. In terms of the definition of response matrix, the corrector strength $\Delta \theta$ can be calculated as

$$\Delta \theta = R_{inv} \cdot \Delta x \,. \tag{1}$$

So the residual orbit error after applying the correction $\Delta \theta \, is^{[4]}$

$$\Delta x' = \Delta x - R \cdot \Delta \theta =$$

$$(I - R \cdot R_{inv}) \cdot \Delta x = A \cdot \Delta x,$$
(2)

where

$$A = I - R \cdot R_{inv} \,. \tag{3}$$

The measured orbit noise is fitted with Gaussian distribution. Fig.5 shows that the close orbit distortion of all BPMs is less than $4.5 \mu m$. The R-square

parameter of orbit noise is shown in Fig.6, which describes the fitness of random data to Gaussian distribution^[5]. The R-square values in No.10 and No.21 BPM are small, and we believe that both of them are affected by slow drift of the beam orbit.



Fig.5 The RMS of orbit noise.



Fig.6 The fitness to Gaussian distribution.

Therefore, it is reasonable to assume that the orbit noise has a Gaussian distribution with zero mean and the same standard deviation σ . Then based on the linear relationship in Eqs.(1) and (2), the corrector strengths and the correction errors also have a zero-mean Gaussian distribution. The standard deviations of the corrector strengths are given by

$$\sigma_i' = \sigma \cdot \sqrt{\sum_{j=1}^n r_{ij}^2} , \qquad (4)$$

where *n* is the number of BPMs and r_{ij} is the element of matrix R_{inv} . The standard deviations of the correction errors are given by

$$\sigma_i'' = \sigma \cdot \sqrt{\sum_{j=1}^n a_{ij}^2} , \qquad (5)$$

where a_{ij} is the element of matrix A.

Let $\sigma = 6 \ \mu m$, the average of the calculated σ_i and σ_i are shown in Fig.7. It shows that the correction errors decrease with the increasing number of the retained eigenvalues, and the corrector strengths increase with the increasing number of the retained eigenvalues.



Fig.7 The calculated correction errors and corrector strengths.

4 The measured correction errors

In the measurement, orbit distortion was randomly generated with a Gaussian distribution with zero mean and the same standard deviation 6 μ m. The corrector strengths were calculated to correct the beam orbit by the inverse response matrix. The correction errors measured are the difference between appointed orbit distortion and the measured orbit changes.

The measured correction errors and corrector strengths are shown in Fig.8. The experiment results agree well with the calculation results. Corrector strength errors, which are not considered in Section 3, might result in the difference between the calculated correction errors and measured correction errors.



Fig. 8 The measured correction errors and corrector strengths.

In Eqs.(4) and (5), the RMS value of the appointed orbit distortion was $\sigma = 6 \ \mu m$. But the measured RMS orbit distortion is less than 4.5 μm from the measured result of Fig.5, the correction errors in Fig.8 can be calculated at around 1 μm when the retained eigenvalue number is 11 or 12. In Fig.4, the smallest eigenvalue of each submatrix is less than 1% of the largest one, and the difference in the order of magnitudes may lead to overload of power supplies of correctors. Therefore, in order to suppress the orbit noise to around 1 μm and to avoid the overload of the corrector strengths, it is suitable to choose 1% of maximum eigenvalue as the singular eigenvalue rejection threshold and retain 11 eigenvalues for each submatrix^[4].

5 Conclusion

SVD algorithm was applied to calculate the inverse response matrix in SSRF FOFB system. The method to generate inverse response matrix proved successful and practical by the testing results. And there was a good match of calculated and measured correction errors. The optimal singular eigenvalue rejection threshold was found.

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