APPLICATION OF ORBIT RESPONSE MATRIX METHOD AT CSNS/RCS

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Abstract

The China Spallation Neutron Source (CSNS) consists of a low energy linac and a high energy Rapid Cycling Synchrotron(RCS). RCS accumulates 80MeV beam and accelerates to 1.6GeV with 25Hz repetition rate and the average extraction beam power is 100kW. For controlling beam loss, the closed orbit should be adjusted as flexible as possible. The orbit response matrix (ORM) method is applied to correct the closed orbit distortion in RCS. The simulation study was made by using the code Linear Optics from Closed Orbit (LOCO) for CSNS/RCS, and the results of simulation study are presented.

INTRODUCTION

The Lattice of RCS is a 4-fold symmetry structure, which consists of 16 triplet cells with circumference of 227.92 m. The Twiss parameters of a super period are shown in Figure 1. As a high intensity accelerator, the beam loss should be strictly controlled to blow 1 w/m [1]. Table 1 shows the main parameters of RCS.

Table 1: Main parameters of RCS

Parameters	Units	Values
Circumference	m	227.92
Repetition Rate	Hz	25
Average current	μ A	62.5
Inj. Energy	GeV	0.08
Ext. Energy	GeV	1.6
Beam Power	kW	100
Nominal Tunes(H/V)	1	4.86/4.78
Acceptance	π mm.mrad	540

The linear optics of real machine often suffered from serious aberration with respect to designed one due to the effective quadruple errors. After correcting the Closed Orbit Distortion (COD) via the Singular Value Decomposition (SVD) method, the quadruple strengths should be calibrated by the LOCO method [2].

CLOSED ORBIT DISTORTION CORRECTION WITH SVD METHOD

In modern high intensity accelerators, there are many kinds of magnet errors can cause Closed Orbit Distortion (COD). Among these errors, the dipole field errors are the most important impact. The beam off the central of the quadruple magnet also observes a dipole field. The beam off the central of the sextuples and octupoles can still see dipole field. This phenomenon is called feed-down effect [3]. In our simulation, magnet imperfections and alignment errors are all considered. The typical tolerances for the alignment and field errors [1] are shown in table 2.

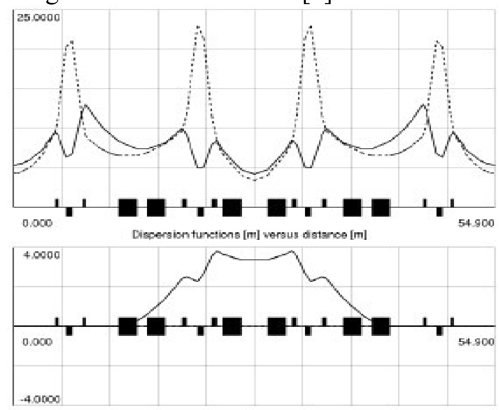

Figure 1: Twiss parameters of a CSNS/RCS super-period.

Table 2: RCS tolerances for the alignment and field error

Alignment and field errors	Tolerances
Girder transverse displacement	0.2mm(rms)
Girder roll	0.2mrad(rms)
Quadruple and sextuple transverse displacement with respect to girder	0.2mm(rms)
Dipoles roll with respect to girder	0.2mm(rms)
Dipole field	2×10^{-4}(rms)

In order to correct closed orbit distortion, SVD method was used in simulation study. The theory of SVD is given below.

Considering a accelerator, including M BPMs and N correctors (steering magnet), the response matrix can be easily obtained by using codes Accelerator Toolbox (AT) [4]. And the closed orbit distortion need to be corrected can be written as:

$$\mathbf{x} = \mathbf{R} * \boldsymbol{\theta}, \quad (1)$$

Where R represents Green function from steering magnets to BPM. And θ represent the steering magnet strength that should be figured out. After given a SVD transform to R, the Eq.1 becomes

$$\mathbf{x} = \mathbf{U} * \mathbf{S} * \mathbf{V}' * \boldsymbol{\theta}, \quad (2)$$

where U, V are the unitary matrix, S represents the singular value of R. By inversing Eq.2, the steering magnet strength can be easily obtained. In order to make the solution meeting the physics reality, some constrained conditions need to be added to Eq.2 or the smallest singular values should be cut off to get a better performance in the inverse process. The last version of steering magnet strength becomes:

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$$\theta = V * (S')^{-1} * U' * x. \quad (3)$$

The figure 2 shows the correction results of COD, in which the horizontal and vertical correctors' strength are below 0.2mrad.

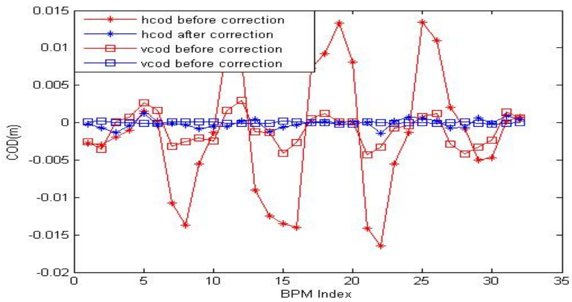

Figure 2: Closed orbit distortion correction. Red line and blue line with star flag represent horizontal and vertical COD before correction respectively; Red line and blue line with square flag represent horizontal and vertical COD after correction respectively.

FITTING RESULTS WITH LOCO

Quadruples, BPM and correctors are the most important fitting parameters in LOCO code. Table 3 shows the components in the RCS.

Table 3: CSNS/RCS components

Dipoles	24
Quadruples	48; with 5 groups
Sextuples	16(4 in each sector)
Horizontal correctors	16(4 in each sector)
Vertical correctors	16(4 in each sector)
BPMS	32(8 in each sector)

BPM Gains is a very sensitive parameter for BPM electrical characteristics. In general, the variation in the BPM gains is below 4%. When this data is larger than the rms value, BPM buttons and cables may have malfunction. In order to verify this process, the 7th and 13th rows of response matrix data were added the opposite sign, which means these two horizontal BPMs polarity has been reversely connected.

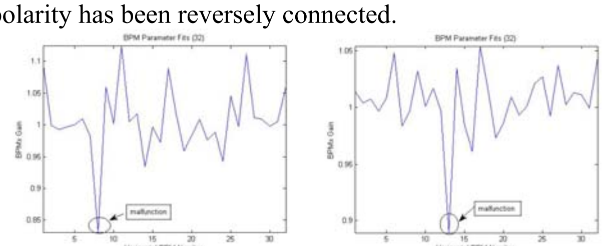

Figure 3: Left: The 7th BPM malfunction is figured out firstly. Right: The 13th BPM malfunction is figured out afterwards.

After these two polarities have been restored, the BPM Gains variation returns to the reasonable values.

The other parameters which can disturb the orbit response matrix are also studied. Quadruple gradient errors (including power supply error), BPM gains, corrector strength, quadruple rotation errors, BPM rotations, correctors longitudinal alignment errors have been carefully simulated. After these errors were added, tunes of the lattice deviate from the nominal point 4.86(H)/4.78(V) to 4.79 (H)/4.91(V), and the beta beating, means that the fractional change of betatron function, come up accordingly. Hereafter, the lattice symmetry was distorted. However, the last three kinds of errors have little contribution to orbit response matrix variation. In other word, when the BPM solution is in the level of 0.1mm, and the noise level is around 0.01m/rad, which means the uncertainty levels of the residual vector elements, the last two kinds of errors contribution was drowned out by the BPM noise. In this case, it is hard to figure out these three errors.

The original Loco fitting algorithm is Gauss-Newton method. Due to the fast convergence, Gauss-Newton method is widely used in most case of locating lattice errors. However, the solution relies on the initial value too much and often finds the unreasonable solution which indicates very large changes to the quadruples strengths ΔK . This may because the resulting lattice model fails to find a closed orbit. Therefore, Gauss-Newton method with weight function was developed to make the solution converge in special direction and make the resulting lattice realistic [2]. Besides, the Levenberg-Marquadt method was also added to the LOCO code. However, Gauss-Newton with weight function method can be cast into the same frame as the Levenberg-Marquate algorithm. Due to the trust region technique adopted, Levenberg-Marquadt method can find the best solution for the iteration within the trust region. Since the trust region is related with the Jacobian matrix generated from response matrix, the solution can be focused step by step via shrinking the trust region. So in the simulation, Levenberg-Marquadt method was adopted.

Chi-square (χ^2) is the index of convergence property, which represents the divergence between fitted lattice and the measured lattice. Fig.4 shows the value of χ^2 in different iteration. χ^2 has been almost descending to zero in the first three iteration.

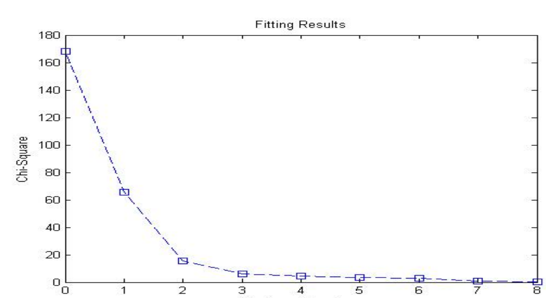

Figure 4: χ^2 values with the iteration number.

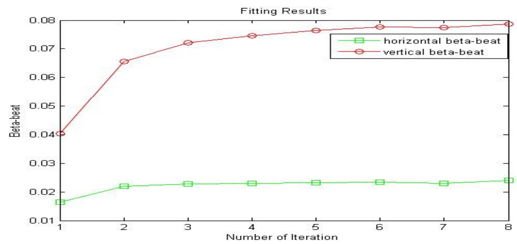

Figure 5: Beta-beating with the iteration number.

The figure 5 shows the beta beatinging in different iterations. Beta beatinging represents the standard deviation of the fractional change of betatron function, which can be obtained from the resulting lattice easily.

Figure 6 gives the results of the 48 gradient errors. Since the power supplies of the quadruples are divided into 5 groups, we fitted the gradient error by group, instead of by position. The error of the power supply is evaluated by averaging the quadruples. The simulated fudge factors are shown in table 4.

Table 4: Fudge Factor of Quadruples

QF01	-0.82%
QD02	0.41%
QF03	-0.55%
QF04	-0.51%
QF05	-0.91%

In order to separate the coupling between BPM scale factor and correctors scale factor. Dispersion must be fitted as a separated column in response matrix, because that the change of correctors' strength has almost no effect on beta function, but have effects on the dispersion. The dispersion function was measured by changing the RF frequency with 80Hz. Figure 7 shows the coupling between BPM scale factor and correctors scale factor. Horizontal BPM scale factor and the corresponding correctors scale factor can be separated while it can not be separated for vertical direction(0.2% BPM scale factor versus -0.2% correctors scale factor), because that the vertical dispersion was not considered. Figure 8 shows the horizontal dispersion fitting results. The measured dispersion differed greatly from the model. After fitting, the agreement is quite good.

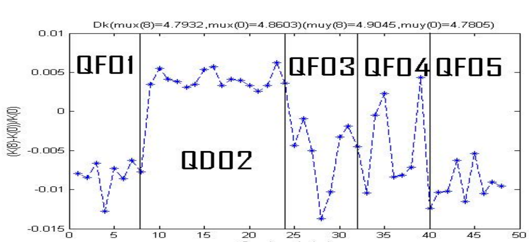

Figure 6: Total relative gradient variations after 8 iteration of the LOCO code. The values are sorted by quadruples families.

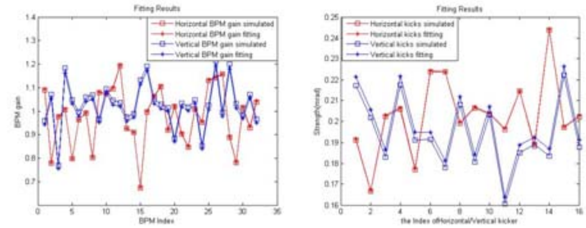

Figure 7: Fitting pattern of BPM and correctors.

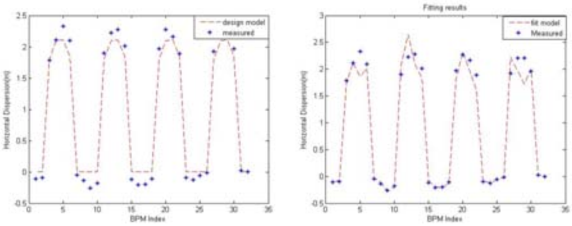

Figure 8: Horizontal dispersion fitting in CSNS/RCS.

CONCLUSION

The process of the correction of Closed Orbit Distortion and optics via response matrix were simulated. The results seem promising. The COD has descended more than 90%. The couplings between BPMs and correctors are also separated. The dispersion fitting results also seems satisfied. Since tunes are often the most convenient parameters to verify the optics calibration [5],The Lattice symmetry is also restored in some degree for the tunes return to 4.88(H)/4.77(V) while the nominal tunes are 4.86(H)/4.78(V).

However, after correcting the optics, the beta beatingings become 0.0017(H)/0.040(V), the reason why beta beatinging in vertical direction is still so large should be carefully considered. In future, we will still optimise the fitting process to separate parameters coupling thoroughly.

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