ORBIT AND OPTICS CORRECTION TO REALIZE DESIGNED MACHINE PERFORMANCE

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Abstract

It is difficult for actual accelerators to achieve the designed machine performance without appropriate correction or adjustment of magnet errors. By correction of magnet errors, we aim to be realized the designed machine performance. However, it is not easy to estimate the design orbit in real accelerators. In KEKB and PF, beam position monitor (BPM) can be calibrated to the center of quadrupole magnet (QM). BPM and QM parallel displacement error referring to design orbit can be estimated using assumption that these errors are coincident. This is, design orbit at BPM and QM can be derived.

ESTIMATION METHOD OF QM PARALLEL DISPLACEMENT ERROR

We use the assumption that BPM and QM parallel displacement error are coincident as Fig. 1. Then, following vector equation is realized

$$\boldsymbol{x_{COD}} = \boldsymbol{x_{BPM}} + \boldsymbol{x_Q} \equiv \boldsymbol{f}(\boldsymbol{x_Q}). \quad (1)$$

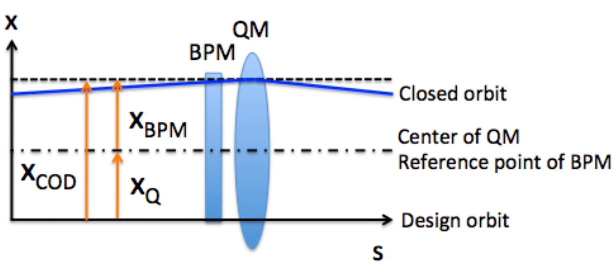

Figure 1: Position relations in terms of QM, BPM, and design orbit.

$\boldsymbol{x_{COD}}$ is closed orbit, $\boldsymbol{x_{BPM}}$ is BPM measurement data, and $\boldsymbol{x_Q}$ is QM parallel displacement error. Since we usually know $\boldsymbol{x_{BPM}}$ as turn-by-turn data and lattice function $\boldsymbol{f}$, $\boldsymbol{x_Q}$ can be estimated using N-dimensional Newton-Raphson method. The repeated calculation is

$$\boldsymbol{x_Q^{k+1}} = \boldsymbol{x_Q^k} + \left(\frac{\partial \boldsymbol{f}(\boldsymbol{x_Q^k})}{\partial \boldsymbol{x_Q^k}} - \boldsymbol{I}\right)^{-1} \{-(\boldsymbol{f}(\boldsymbol{x_Q^k}) - \boldsymbol{x_Q^k}) + \boldsymbol{x_{BPM}}\}. \quad (2)$$

$\boldsymbol{k}$ is repeated number and $\boldsymbol{I}$ is unit matrix. The vector equation includes not only horizontal direction but also vertical direction.

CONDITION NUMBER

For estimation of $\boldsymbol{x_Q}$, inverse matrix has to be calculated. Condition number plays important role in the case [1]. Condition number shows how much errors are propagated. Ordinarily, condition number is given by maximum singular value divided by minimum singular value. If condition number is very large, estimated values are often different from real values. In such case, by setting threshold with respect to singular value, approximated values can be obtained. There are some methods for singular value truncation. We use following method,

$$\omega_i = \begin{cases} \omega_i \ (\omega_{min}/\varepsilon > \omega_i) \\ 0 \ (\omega_{min}/\varepsilon \leqq \omega_i) \end{cases}. \quad (3)$$

ε is threshold, ω_i is singular value of inverse matrix, ω_{min} is minimum singular value of inverse matrix.

ESTIMATION OF MAGNET ERRORS

We consider that QM has parallel displacement error $\boldsymbol{x_Q}$ and rotation error $\Delta\boldsymbol{\theta_Q}$ and magnetic error $\Delta\boldsymbol{k_Q}$ and sextupole magnet (SM) has parallel displacement error $\boldsymbol{x_S}$.

- First, these errors are given to SuperKEKB design lattice, using SAD [2]. In this paper, we call the value "setting value". In the calculation, these errors have Gaussian distribution. Typical amplitudes of those errors are chosen as $(x_Q, \Delta\theta_Q, \Delta k_Q/k_Q, x_S) = (5\times10^{-5}\text{m}, 4\times10^{-5}\text{m}, 3\times10^{-4}\text{rad}, 7\times10^{-4})$ [3].
- Second, $\boldsymbol{x_Q}$ is estimated from closed orbit using the method mentioned previous section.
- Third, QM parallel displacement error is changed by $-\boldsymbol{x_Q}$.
- Forth, $\Delta\boldsymbol{\theta_Q}$, $\Delta\boldsymbol{k_Q}$, and $\boldsymbol{x_S}$ are estimated from optics parameters.
- Fifth, QM rotation error, QM magnetic error, and SM parallel displacement error are changed by $-\Delta\boldsymbol{\theta_Q}$, $-\Delta\boldsymbol{k_Q}$, and $-\boldsymbol{x_S}$, respectively, and emittance is shown using some seed for random number.

Needless to say, magnet errors given by us are not used in magnet errors estimation.

Estimation of QM Parallel Displacement Error

Frequently, convergence of Newton-Raphson method is failed in large error amplitude even if truncated singular values are used, especially SuperKEKB which has large nonlinearity. In the case, it is necessary to devise some better methods. For example, estimation is done using linearized lattice at first; next, result of the estimation is adopted initial value $\boldsymbol{x_Q}$ of Newton-Raphson method, estimation is done using original lattice at last.

Fig. 2 shows estimation result of QM parallel displacement error. Even if there are $\Delta\boldsymbol{\theta_Q}$, $\Delta\boldsymbol{k_Q}$, and $\boldsymbol{x_S}$,

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estimation of $\boldsymbol{x_Q}$ work well. That is, these error parameters do not affect orbit very much in SuperKEKB.

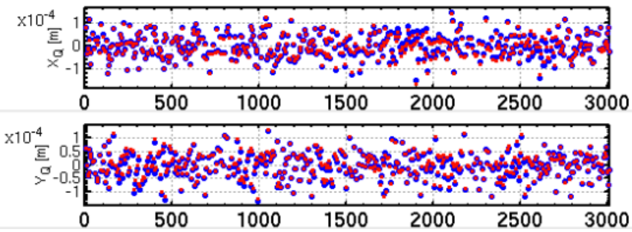

Figure 2: QM parallel displacement error. Blue point is setting value and red point is estimated value. Horizontal axis is described by longitudinal direction.

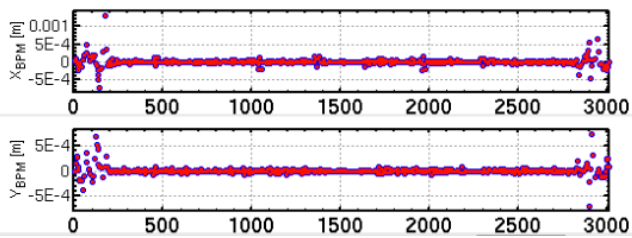

Figure 3: Measurement data at BPM in presence of setting value of QM parallel displacement error (Blue) and in presence of estimated value of its error (Red).

Estimation of QM Rotation and Magnetic Error and SM Parallel Displacement Error

Estimation method of QM rotation and magnetic error and SM parallel displacement error is similar to the estimation method of QM parallel displacement error. In case of QM parallel displacement error,

$$\boldsymbol{x_{BPM} = f(x_Q) - x_Q}. \quad (5)$$

While, in case of QM rotation and magnetic error and SM parallel displacement error,

$$\boldsymbol{(R_1, \beta_x, \beta_x, \eta_y) = h(\theta_Q, k_Q, x_S)}. \quad (6)$$

R1 is one of x-y coupling parameter, β_x and β_y are horizontal and vertical beta function, respectively, and η_y is vertical dispersion function.

Fig. 4 shows estimation result of QM rotation and magnetic error and SM parallel displacement error and Fig. 5 shows Optics parameters measured by turn-by-turn BPM. In the figure, estimated value is different from setting value even optics parameters for estimated value are correspond to that for setting value. This is mainly because these errors cannot be determined by effect of these errors to optics parameters using BPM which number is same to the number of QM. As far as nonlinearity is small around beam orbit, optics correction works well to change these errors by these estimated values. Nonlinearity reduction had already done by correction for QM parallel displacement error.

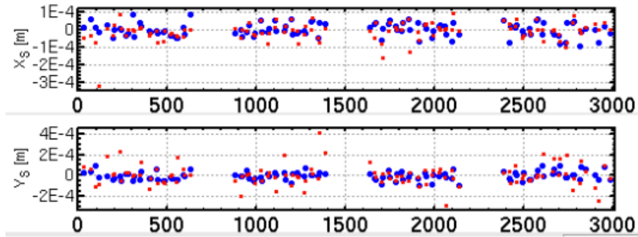

Figure 4: SM parallel displacement error. Blue point is setting value and red point is estimated value.

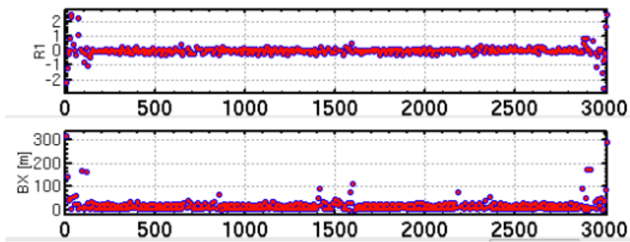

Figure 5: Optics parameters measured by turn-by-turn BPM in presence of setting value of SM parallel displacement error, QM rotation error, and QM magnetic error (Blue) and in presence of estimated value of those error (Red) [4]. R1 is one of x-y coupling parameter and BX is horizontal beta function.

Fig. 6 shows optics parameters before orbit and optics corrections and after orbit and optics corrections. R_1 and η_y are very large before the corrections, while the optics parameters are almost zero after the corrections.

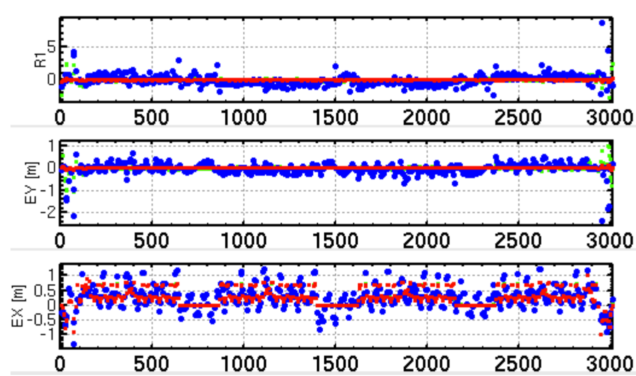

Figure 6: Optics parameters before orbit and optics corrections (Blue) and after orbit and optics corrections (Red). EX and EY are dispersion functions.

Emittance Comparing

Table 1, 2, and 3 show emittance before the corrections, emittance after orbit correction, and emittance after orbit and optics corrections for some seed. Emittance for SuperKEKB design lattice is $(\varepsilon_x, \varepsilon_y, \varepsilon_z) = (3.0\times10^{-9}, 9.1\times10^{-13}, 4.1\times10^{-6})$ m. Target value of vertical emittance in SuperKEKB is about $6\sim7\times10^{-12}$m. Table 2 show that only orbit correction is not enough to

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realize target value of vertical emittance. After orbit and optics corrections, vertical emittance becomes small enough.

Table 1: Emittance before Corrections for Some Seed

ε_x [m]	ε_y [m]	ε_z [m]
1.5×10^{-8}	3.5×10^{-9}	4.4×10^{-6}
1.4×10^{-8}	3.9×10^{-9}	4.0×10^{-6}
1.5×10^{-8}	2.8×10^{-9}	4.2×10^{-6}

Table 2: Emittance after Orbit Correction for Some Seed

ε_x [m]	ε_y [m]	ε_z [m]
3.2×10^{-9}	1.4×10^{-11}	4.1×10^{-6}
3.9×10^{-9}	9.3×10^{-11}	4.1×10^{-6}
3.4×10^{-9}	1.3×10^{-10}	4.1×10^{-6}

Table 3: Emittance after Orbit/Optics Corrections for Some Seed

ε_x [m]	ε_y [m]	ε_z [m]
3.0×10^{-9}	2.3×10^{-12}	4.1×10^{-6}
3.0×10^{-9}	2.2×10^{-12}	4.1×10^{-6}
3.1×10^{-9}	1.3×10^{-12}	4.1×10^{-6}

ESTIMATION OF MAGNET ERRORS EXCEPT FOR QM PARALLEL DISPLACEMENT ERROR

Fig. 7 shows optics parameters before optics correction and after optics correction. Orbit correction is not performed. Optics parameters are not corrected after "optics correction". This is because nonlinearity around beam orbit is still large. Clearly, vertical emittance is also large as shown Table 4. Orbit correction is necessary for SuperKEKB in this method.

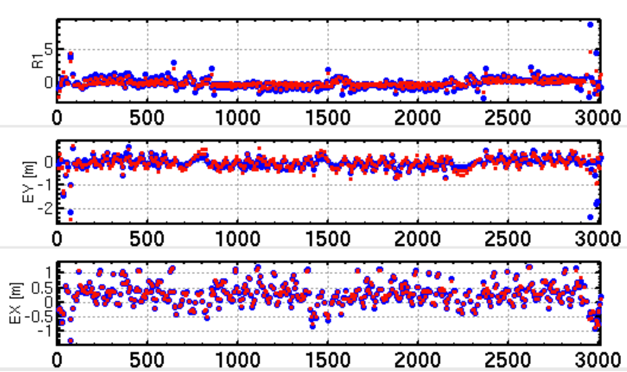

Figure 7: Optics parameters before optics correction (Blue) and after optics correction (Red).

Table 4: Emittance after Only Optics Correction for Some Seed

ε_x [m]	ε_y [m]	ε_z [m]
1.4×10^{-8}	3.3×10^{-9}	4.3×10^{-6}
1.3×10^{-8}	5.3×10^{-9}	4.1×10^{-6}
1.4×10^{-8}	3.1×10^{-9}	4.2×10^{-6}

CONCLUSION

We consider that QM has parallel displacement error and rotation error and magnetic error and SM has parallel displacement error. These errors are estimated and corrected well after orbit and optics corrections. Some of optics parameters and vertical emittance is small enough after the corrections. On the other hand, optics parameters and vertical emittance are still large after optics correction unless orbit correction is performed. This shows QM parallel displacement error correction is necessary for the lattice, which has large nonlinearity like SuperKEKB.

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