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PARALLEL QUADRUPOLE MODULATION FOR FAST BEAM-BASED DETERMINATION OF MAGNET CENTERS *

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Abstract

A new method to perform parallel beam-based alignment is described. The method uses the orbit response matrix from kicks applied at quadrupole locations to the beam position monitors to determine the kick angles by the quadrupoles as they are modulated. The measurement is repeated as the orbit at the quadrupoles are changed. The magnet center is found by fitting the kick angle versus the orbit data to a linear curve for the zero-crossing point. The method has been experimentally demonstrated on a storage ring. It can also been applied to sextupole magnets.

INTRODUCTION

The "bow-tie" method [1] is commonly used for beam-based alignment (BBA) measurement on storage rings. It determines the magnetic center of a quadrupole magnet by modulating its strength while measuring the orbit changes on beam position monitors (BPM). The measurement is repeated as the orbit at the quadrupole is changed by a selected corrector magnet. The orbit changes on the BPMs due to the magnet strength modulation depend on the orbit at the quadrupole linearly. By fitting the orbit changes at BPMs with respect to the orbit at quadrupole location, one can find the zero-crossing point, where magnet modulation does not cause orbit changes. The zero-crossing point corresponds to the magnetic center of the quadrupole. This method is also referred to as the quadrupole modulation system (QMS) method as in the Matlab Middle Layer (MML) [2].

The QMS method is mature and reliable. However, it is a slow measurement. For example, on SPEAR3, it takes about 150 minutes for 60 quadrupole magnets, with fast corrector magnets and dedicated, fast power supply for the quadrupoles. The PBBA method [3] has been proposed to perform fast BBA measurement. It aims at correcting the induced orbit shift (IOS) due to magnet modulation using corrector magnets. The IOS response matrix of the selected corrector magnets are used to solve for the desired orbit changes. Centers for multiple magnets can be found simultaneously as the correction of IOS brings the orbit toward the centers of the magnets. The PBBA method is much faster than the original QMS method.

In this report, we describe a different method for fast, parallel BBA. This method will be called parallel QMS (P-QMS), as it resembles the original QMS, but applicable to a group of quadrupoles. The P-QMS utilizes the quadrupole location-to-BPM orbit response matrix to determine the kicks applied by the quadrupoles as they are modulated and is able to separate the contributions of the individual quadrupoles to the IOS.

The P-QMS method can be used for both storage rings and one-pass systems. The application of the basic principle to a one-pass system has been previously reported in Ref. [4]. In this report, we present the method systematically and show its application on a storage ring. The initial application to a ring was done by using two corrector magnets to steer the orbit in the quadrupoles. A later improvement was made by using local orbit bumps for the quadrupoles. The P-QMS method has also been extended for application to sextupole magnets.

THE P-QMS METHOD

In the original QMS method, the IOS is measured as the orbit at the targeted quadrupole is changed. The IOS vs. orbit at the BPMs are fitted to linear curves to find the zero-cross point, which corresponds to the quadrupole center. This method cannot be used for more than one quadrupole as their contributions to the IOS are mixed.

The P-QMS addresses the difficulty by first calculating the kick angles from the IOS using the orbit response matrix from kicks at the quadrupole locations to BPMs, $\mathbf{R}_q$. Suppose N_q quadrupoles are modulated simultaneously and there are M BPMs, the matrix is $M \times N_q$ in dimension. With the measured IOS, $\Delta\mathbf{x}$, the corresponding kicks by the N_q quadrupoles can be found by inverting the response matrix,

$$\Delta\boldsymbol{\theta}_q = \left(\mathbf{R}_q^T\mathbf{R}_q\right)^{-1}\mathbf{R}_q^T\Delta\mathbf{x}. \tag{1}$$

The elements in the $\Delta\boldsymbol{\theta}$ vector represent the kick angles by the individual quadrupoles in the group being modulated. The matrix $\mathbf{R}_q^T\mathbf{R}_q$ needs to be full rank for the scheme to work. This should not be an issue if one can choose the group of quadrupoles to modulate simultaneously. In such a case, one would choose quadrupoles separated by enough BPMs and correctors.

The kick angle by a modulated quadrupole depends on the change of integrated gradient as it is modulated and the distance between the orbit and the quadrupole center,

$$\Delta\theta_{q,i} = \Delta K_i L_{q,i}(x_{q,i} - \bar{x}_{q,i}), \tag{2}$$

where ΔK_i is the change of normalized gradient by the modulation, $L_{q,i}$ the length of the quadrupole, $\bar{x}_{q,i}$ the magnetic center of the quadrupole, and $x_{q,i}$ the orbit at the quadrupole. Fitting $\Delta\theta_{q,i}$ vs. $x_{q,i}$ and finding the zero crossing, the quadrupole center can be determined.

The response matrix $\mathbf{R}_q$ is obtained by calculation with a lattice model. Because of optics errors in the real machine, the calculated response matrix would differ from that of the

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real machine. However, the difference is usually acceptable, even for a machine during the commissioning phase. This is especially true if only BPMs near the modulated quadrupoles are used to determine the kick angles. In addition, the difference may cause an error to the calculated kick angle, but it will not change the zero-crossing location. Therefore, the quadrupole centers can be found in a few iterations.

The orbit change at the quadrupole locations can be introduced with corrector magnets. In the original QMS method, one corrector suffices as we only need to change the orbit at one location. However, one corrector would not be enough for a group of quadrupoles as some magnets may be close to $m\pi$ away in betatron phase advance from the corrector and thus sees little orbit shift. One solution to the problem is to use two corrector magnets, with a phase advance of about $\frac{\pi}{2}$ (modulo π) in between. Such a pair of correctors can guarantee a sufficiently large orbit shift be made at all quadrupole locations.

A better approach would be to make orbit changes with closed orbit bumps at the quadrupole locations. This approach has several advantages. First, only a half of the IOS measurements are needed compared to the case with two correctors. Second, the local bumps keep the orbit distortion in the vicinity of the targeted quadrupoles and thus the feed-down effects at other magnets are minimal.

EXPERIMENTS ON SPEAR3

The P-QMS method has been tested on the SPEAR3 storage ring. Figure 1 shows an example of the measured IOS for a group of 14 QF quadrupoles, one from each standard cells. The quadrupoles are modulated with alternate signs to keep the betatron tunes nearly fixed. The IOS is measured with the bipolar method, i.e., by flipping the sign of modulation and subtracting the orbit differences. The corresponding kick angles calculated are shown in the bottom plot. Dashed lines in the upper plot show the calculated IOS in comparison to the measurement. It can be seen that the measured IOS is well accounted for with the calculated kicks. It is worth pointing out that the approach of calculating kick angles by the modulated magnets helps isolate the effects of orbit drift or distortions by other sources during the IOS measurements as such effects usually do not correspond to the magnets being modulated.

In earlier tests, two correctors are used to steer the orbit at quadrupole locations. Figure 2 top plots show the kick angles vs. the orbit at the magnet location (as seen by a nearby BPM) for one of the quadrupole in the group. As each corrector steers the orbit to 5 positions, there are a total of 10 data points. The center of the quadrupole is found by fitting the kick angles with respect to the orbit to a linear curve.

In a more recent test, local orbit bumps are used to steer the orbit at the quadrupole locations. The orbit bump is calculated with the lattice model using the ordinary orbit response matrix. There are 3 correctors for each standard cell. Because of the particular values of the betatron phase

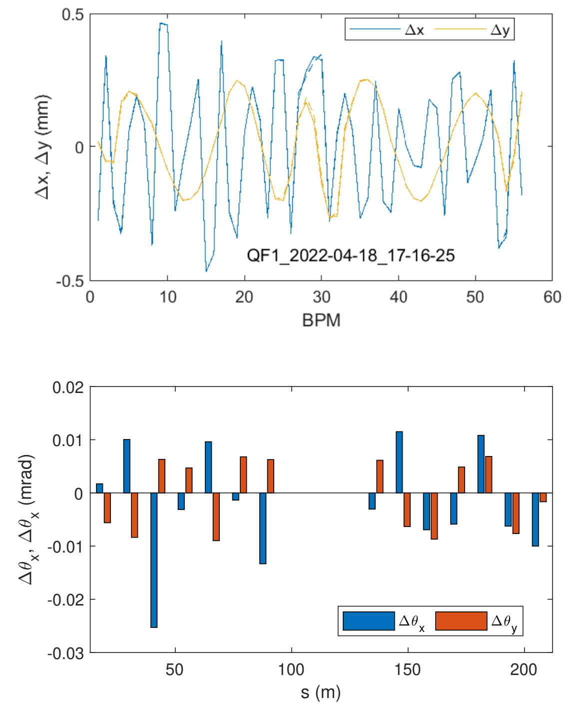

Figure 1: The measured IOS (top) and the corresponding kick angles (bottom) calculated from it for a group of 14 QF quadrupoles on SPEAR3.

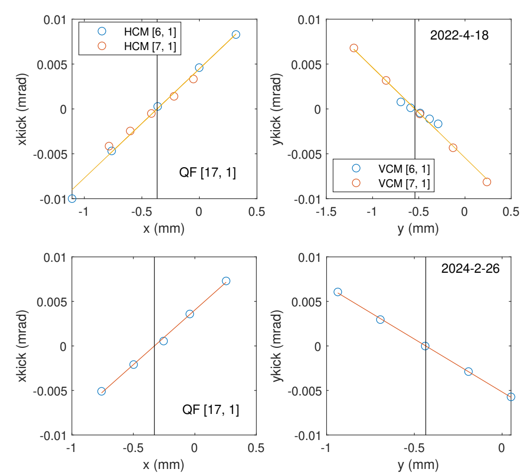

Figure 2: Fitting kick angle vs. orbit at quadrupole QF [17, 1] when two correctors are used (top) or closed orbit bumps are used (bottom). The orbit is measured by a BPM located next to the magnet. The two data sets are taken about two years apart in time.

advances for each cell, it is relatively easy to create local bumps in the horizontal plane and more difficult for the vertical plane. Adding weights to BPMs and selecting the right number of singular values for matrix inversion can help make the orbit bumps. Figure 3 shows the orbit bumps in one measurement. The bottom plots in Fig. 2 shows the kick angle vs. orbit data using orbit bumps.

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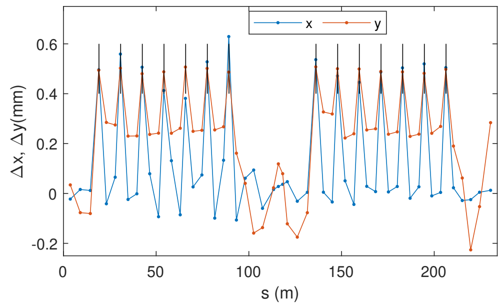

Figure 3: The measured orbit bumps for the 14 QF quadrupoles whose locations are marked by the vertical bars.

The P-QMS measurements were repeated 5 times on the same shift with different starting orbit. The 28 QF magnets from 14 standard cells are divided two groups. The original QMS measurement was also done. Figure 4 compares the P-QMS and QMS results. The error bars for P-QMS are estimated with the standard deviation of the 5 data sets. The average error bar size is 22 μm for the horizontal plane and 13 μm for the vertical plane. The large error bars correspond to cases when the magnetic center is not covered by orbit range for some data sets.

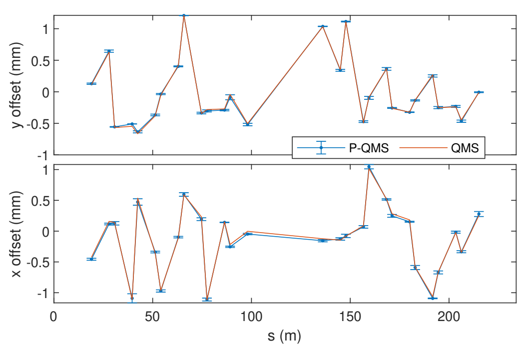

Figure 4: The magnetic centers of 28 QF magnets determined by P-QMS with different initial orbit are compared to results by the original QMS.

APPLICATION TO SEXTUPOLES

Reference [3] describes the method to find sextupole centers by minimizing the IOS due to modulation of the strengths of a group of sextupole magnets. The method has been experimentally demonstrated on the SPEAR storage ring. An example is shown in Fig. 5, where the horizontal centers of the 8 SFM sextupoles in the four matching cells are targeted simultaneously, using 4 combined steering knobs made of 12 corrector magnets. The sextupole magnets share a common power supply. The top plot shows the history of the objective function, defined as the sum of squares of IOS measured by all BPMs when the sextupole strength is reduced by 20%, as it is minimized by the RCDS algorithm [5]. The bottom plot shows the IOS before and after minimization.

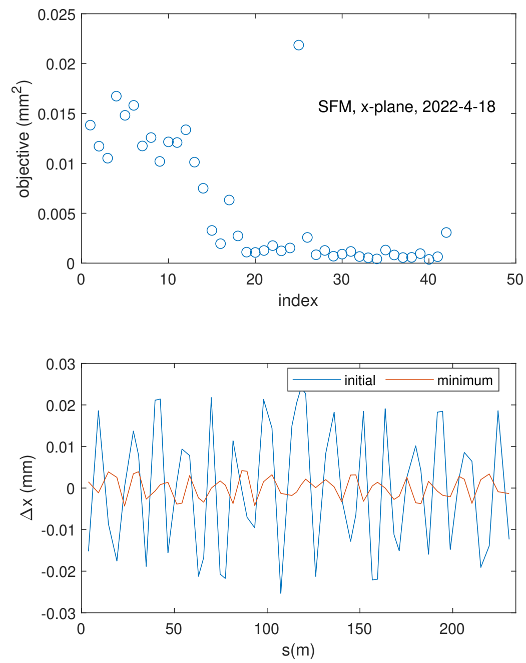

Figure 5: Experimental demonstration of sextupole PBBA on SPEAR3 using the SFM sextupole family.

The PBBA method for sextupoles by minimizing the total IOS of a group of magnets does not scale well to larger groups as more function evaluations are needed when the number of knobs increase. The principle of obtaining the individual kick angles by the magnets with orbit response matrix, as adopted in the P-QMS method, can be used to substantially speed up the PBBA method for sextupoles. One can define a local orbit bump for each sextupole and use it as the knob to minimize the magnitude of the kick angle by the magnet. Therefore, the minimization of IOS by a group of N sextupoles can be parallelized as $2N$ 1-dimensional (1 knob, 1 objective) optimization problem.

SUMMARY

The P-QMS method is proposed to perform parallel BBA for a group of quadrupoles. It is based on calculating the kick angles by the magnets due to modulation of their strengths with the quadrupole location to BPM orbit response matrix. Local orbit bumps are used to steer the beam at the magnets and the kick angle vs. orbit fitting is used to determine the zero-crossing point, which corresponds to the magnetic center. The method has been demonstrated on the SPEAR3 storage ring with good agreement with the traditional QMS method. The idea can be applied to speed up the PBBA method for sextupole magnets.

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