DISPERSION AND BETATRON FUNCTION CORRECTION IN THE ADVANCED PHOTON SOURCE STORAGE RING USING SINGULAR VALUE DECOMPOSITION*

L. Emery, ANL, Argonne, IL

Abstract

Magnet errors and off-center orbits through sextupoles perturb the dispersion and beta functions in a storage ring (SR), which affects machine performance. In a large ring such as the Advanced Photon Source (APS), the magnet errors are difficult to determine with beam-based methods. Also the non-zero orbit through sextupoles result from user requests for steering at light source points. For expediency, a singular value decomposition (SVD) matrix method analogous to orbit correction was adopted to make global corrections to these functions using strengths of several quadrupoles as correcting elements. The direct response matrix is calculated from the model of the perfect lattice. The inverse is calculated by SVD with a selected number of singular vectors. Resulting improvement in the lattice functions and machine performance will be presented.

1 INTRODUCTION

The lattice functions (β_x, β_y, η_x, and η_y) in the APS storage ring are perturbed from those of the ideal model because of possible quadrupole calibration errors and off-center orbits through the sextupoles. It is desirable to correct these lattice functions because they have some impact on machine performance such as injection efficiency, dynamic aperture, momentum aperture (for Touschek lifetime), tune adjustment, and orbit correction.

There exist beam-based methods that achieve the above goal by first determining an accurate model of the ring from a fit to experimental data, then making changes to the quadrupole magnet setpoints to compensate for the calibration errors (see for example [1]). The machine functions after correction agree well with the ideal.

The above method and similar methods are difficult to apply to the APS storage ring for several reasons. For one, the strong sextupoles in the APS ring can potentially produce a significant focusing magnetic field that confuses with the nearby quadrupoles. When the method has been applied to smaller rings as in [1], the sextupoles were eliminated from the fitting process by simply turning them off and making measurements with a stored beam with uncorrected chromaticity. The APS ring has such a large natural chromaticity that the beam cannot be stored when the sextupole magnets are turned off. If the sextupoles are left on, the focusing effect of the sextupoles could be included as a known quantity in the fitting by suppying the horizontal beam position through the sextupoles. However, determining accurate positions of the beam relative to sextupole magnetic centers is not a trivial measurement.

Another fitting method uses measurements of several trajectories through parts of the ring made linear by turning sextupoles off [2]. Since the APS ring can store beam with at least two of the 40 sectors with sextupoles turned off, this method initially held promise. However, the difficulty here is the confounding of the calibration factors of quadrupoles with the gain errors of the beam position monitors.

We decided to adopt a philosophy similar to orbit correction where we make corrections to the lattice functions directly without identifying the source of errors, even though it is clear what kinds of magnet errors produce lattice function perturbations. We measure the lattice function errors and determine corrections by applying a change in setpoints to a small set of magnets. This idea is particularly applicable to the APS storage ring since all quadrupoles are individually controlled. It is hoped that the goal of improving machine performance can be attained by reducing the lattice perturbation globally and not necessarily by making a complete correction at all points around the ring.

2 METHODOLOGY

Though one may guess that the correction of the lattice functions to be more complex than orbit correction, the process is mathematically analogous to orbit correction because the perturbations of the lattice functions are derived from similar differential equations with driving terms linear in some magnet error (for β the relevant quantity that obeys a linear differential equation is $(\Delta\beta/\beta)$ [3]). Any such formulation can be turned into a matrix correction algorithm for use in a control system operator interface.

As in orbit correction, the correction setup requires first calculating a response matrix in which each element corresponds to the response a measurement quantity makes to the action of a control quantity. For example, in the η_x correction the measurement quantity is the dispersion measured at the SR beam position monitors (BPMs) and the control quantities are quadrupoles in the dispersion matching section. The response matrix is then inverted using singular value decomposition, a standard matrix inversion algorithm that allows some flexibility in controlling the amount of correction and stability of correction. For instance, selecting only a small number of the largest singular values (SVs) reduces the ability to correct the short wavelength features, but tends to stabilize the correction in the presence of measurement errors or model inaccuracies.

The response matrix is constructed by combining the results of several calculations, each using a baseline model of

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the ring plus a small change in one particular magnetic element representing the control quantity. The `elegant` [4] code was used to make the calculations. The output data (lattice functions) is written in the Self-Describing Data Sets (SDDS) file format [5, 6], which comes with a powerful postprocessing toolkit. For each lattice function to be corrected, Tcl/Tk scripts composed of postprocessing commands generate the response matrix, the inverse response matrix, and a magnet setpoint delta file to write to the accelerator control system.

The corrections were applied separately to the lattice functions in APS storage ring. Correcting all lattice functions simultaneously can be done in principle using an all-inclusive matrix. Correcting only β_y, say, could affect η_x since quadrupoles are control quantities for both lattice functions. Considering the main harmonic component of each lattice perturbation, it is hoped that correction interaction between the lattice functions is not significant. For the APS ring, where $\nu_x = 35.2$ and $\nu_y = 19.3$, the 35th harmonic of quadrupole correction dominates the η_x correction, the 70th harmonic dominates the β_x correction, and the 38th and 39th harmonics dominate β_y. Since η_y uniquely uses the skew quadrupoles, η_y remains corrected after any regular quadrupole change.

In addition, one can reduce the possible interaction by selecting quadrupoles at "good" locations as correctors for each lattice function. For instance, β_x should be corrected using quadrupoles where $\beta_x > \beta_y$ and $\eta_x = 0$.

A practical aspect is the time required for collecting measurement data. Since lattice functions are physically derived quantities, the correction could take a shift. Pre-existing Tcl/Tk applications are used to measure η and β and write results to a file. It takes about one minute to make dispersion function measurements at all SR BPMs (which number greater than 360). The β readback consists of a sequence of relatively accurate β measurement at quadrupole positions, each taking 5 to 7 minutes for both β_x and β_y. Therefore, to make several correction iterations practical, the β readback can only consist of a handful of β values spread uniformly around the ring. One must assume that the readbacks sample a smooth global perturbation consisting of a few harmonics such that reducing the perturbation at the measurement points with a few-SVs correcting matrix will reduce the perturbation at all points.

Another operational issue is the requirement of standardizing the quadrupole magnets after every correction before making another lattice function measurement.

3 RESULTS

The current unperturbed lattice functions for the APS sector are shown in Figure 1. The ten quadrupoles in the sector are designated A:Q1 through A:Q5, then B:Q5 to B:Q1. Figure 2 shows the perturbed η_x with a dominant harmonic at the integer tune of 35 appearing as a 5-period modulation due to the 40-fold symmetry of the lattice.

The dispersion correction uses all SR BPMs, and 40 A:Q5-B:Q5 quadrupole pairs as 40 individual correctors.

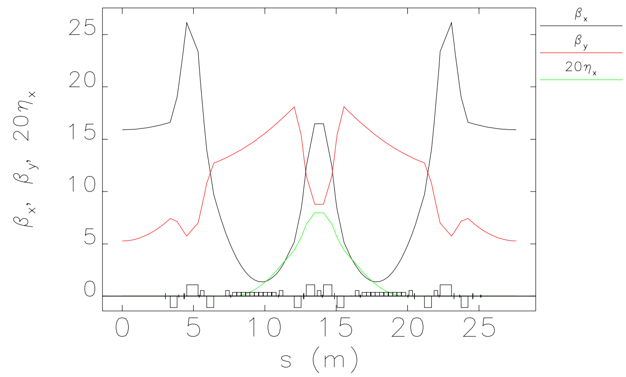

Figure 1: APS sector lattice functions

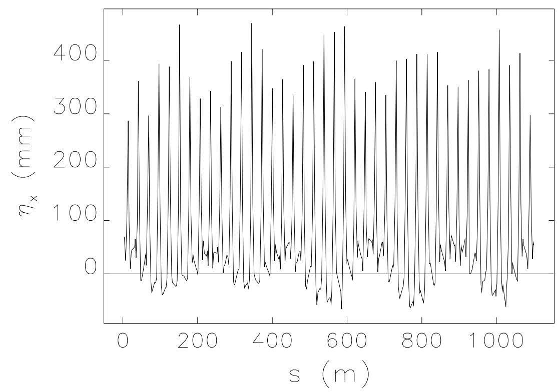

Figure 2: Original dispersion

Using all 40 SVs for the matrix inversion gave a stable correction probably due to the large ratio of number of readbacks to correctors. After several iterations, the η_x perturbation rms was reduced from 37 mm to 7 mm. The η_x at one location measured in each sector (Figure 3) clearly shows the reduction of the 35th harmonic component. The amplitude of quadrupole relative strength change was about $\pm 6 \times 10^{-3}$. After the correction the beam lifetime improved from 28 hours to 37 hours for the standard user fill pattern, presumably due to an indirectly-caused increase in momentum aperture (not measured). The emittance in both planes did not change appreciably.

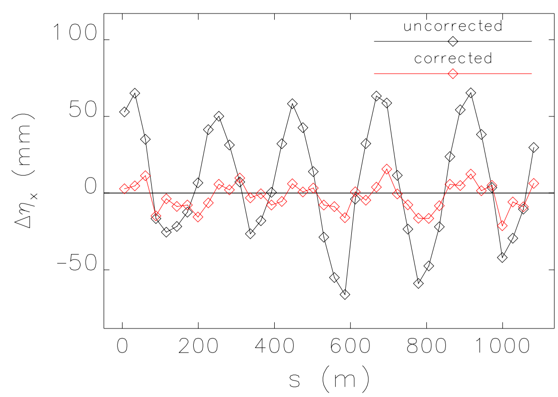

Figure 3: Reduction in η_x error by matrix correction

It is expected that correcting the vertical dispersion will reduce the vertical emittance and xy coupling of the stored beam. Also, the injection losses from incoming particle motion growing in y will be reduced.

There are 19 skew quadrupoles distributed around the ring and available as correctors. (A 20th skew quadrupole was removed because of a redesign of a vacuum chamber.) Ten of the skew quadrupoles are located in the η_x matching section (near A:Q4), and the other nine are in a nominally dispersion-free section (near B:Q3). The SVD matrix inversion automatically eliminated the latter nine since they have no effect on η_y.

Given that there are about 360 dispersion measurement points and only nine independent correctors, the correction can be made with as many as nine SVs. Trying eight SVs for the matrix inversion produced large skew quadrupole setpoint changes, and caused a divergence in η_y and a noticeable tilt on the synchrotron light beam image. This is surprising given that the ratio in the number of readbacks and correctors is large. There may be significant error due to small xy coupling in the BPMs. Also the skew quadrupole-to-η_y response matrix may be sensitive to errors in the phase difference between the x and y motion. The corrections made with four SVs gave more reasonable results, which demonstrates the flexibility of SVD decomposition. Figure 4 shows the overall improvement of η_y. The minimum rms achieved was 2.4 mm, a threefold reduction in this case. According to lifetime measurements, the vertical emittance was reduced by approximately a factor of two, making the ratio to horizontal emittance about 0.3%.

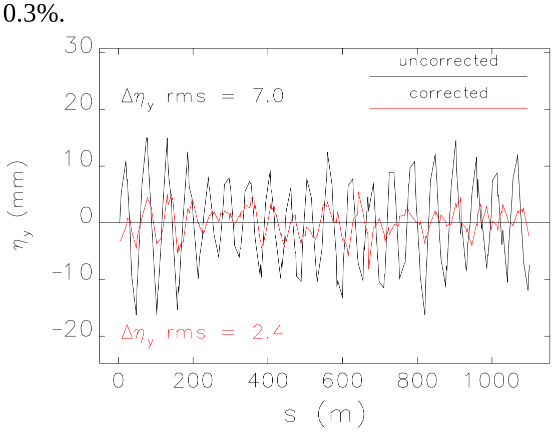

Figure 4: Reduction in η_y by matrix correction

The β_x perturbation of the ring was relatively small. Figure 5 shows the measured β_x and β_y at A:Q1s in every other sector around the ring. On this plot, a 70th harmonic in β_x perturbation should appear as a 10th harmonic, which is not evident. Thus no attempt was made to correct β_x.

A large β_y modulation is observed and is a suspected cause of injection losses at the small vertical apertures. Correcting the modulation in β_y will maximize the vertical acceptance of the 5-m-long small aperture vacuum chambers. The full β_y measurement takes a prohibitively long time to perform. Nevertheless an efficient set of measurement locations must be adopted. During initial tests, various small numbers of points (4 and 8) were used, which

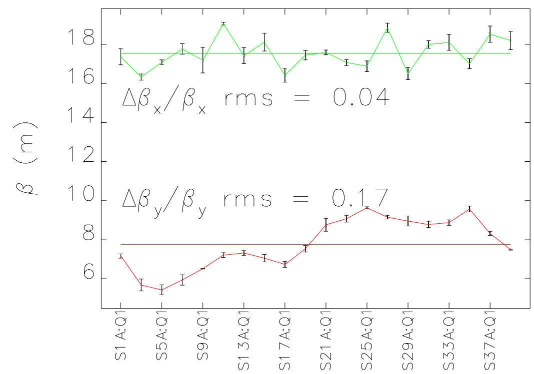

Figure 5: β modulation at several A:Q1 quadrupoles

turned out to be insufficient in representing the overall perturbation. As a compromise, readings at 12 A:Q1s are taken, the A:Q1s being selected for their proximity to the small vertical apertures. The control quadrupoles selected are the 40 A:Q4s, which have $\beta_y > \beta_y$.

There was not much opportunity to test various numbers of SVs for β correction. Figure 6 shows the resulting β_y at 12 measurement points from using 8 SVs on the original 20 readbacks, then 8 SVs again with the same 12 readbacks. The modulation was reduced from 17% to 9%. The short wavelength modulation that remains appears to be outside the range of the global correction.

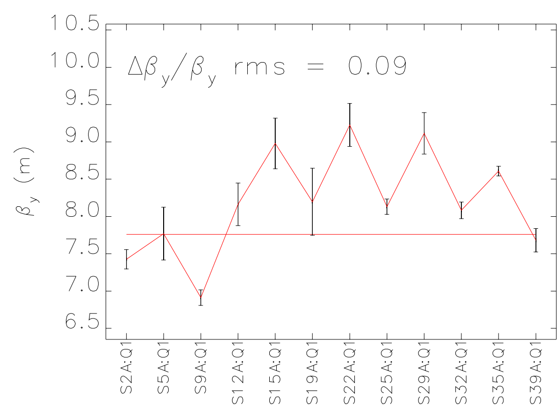

Figure 6: β_y modulation after correction

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