APPLICATION OF MODEL-INDEPENDENT ANALYSIS USING THE SDDS TOOLKIT*

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Abstract

The model-independent analysis (MIA) method in accelerators has not yet come into widespread use, unfortunately. This is perhaps due to a lack of convenient tools to bring the measurement data to the results stage. At the Advanced Photon Source, we used the SDDS Toolkit and the SDDS-compliant EPICS Toolkit in simple and not-so-simple applications for diagnosing operational problems from beginning to end in a short time. We were able to make quantitative measurements of pulsed power supply noise and beam position monitor noise, and identify an unstable power supply.

INTRODUCTION

Model-independent analysis (MIA) was introduced a few years ago as an implementation of Principal Component Analysis, a statistical analysis method that extracts essential signals from noisy but correlated sampled data [1]. MIA has been applied to the SLAC linear accelerator [1] and the PEP-II [2] and Advanced Photon Source (APS) rings [3] to identify spatial modes (trajectory-like patterns) in beam position monitor (BPM) data and their time dependence. Since this type of study involves both data acquisition and numerical analysis, it is natural to integrate these parts using the SDDS Toolkit [4] and the SDDS EPICS Toolkit [5].

This paper will give examples of the SDDS Toolkit implementation in quantifying some operational problems at APS. The theory of MIA has already been covered in [1], so we won't repeat it here. We'll simply give a description of the steps.

Using the notation of [6], we take P samples of M synchronized BPMs, $\mathbf{b}(t_p) = (b_p^1, b_p^2, \ldots b_p^M)$, and arrange the data as a matrix,

$$\mathbf{B} = \begin{pmatrix} b_1^1 & b_1^2 & \cdots & b_1^M \\ b_2^1 & b_2^2 & \cdots & b_2^M \\ \vdots & \vdots & \ddots & \vdots \\ b_P^1 & b_P^2 & \cdots & b_P^M \end{pmatrix}. \quad (1)$$

Using singular value decomposition (SVD), this matrix $\mathbf{B}$ is factored into a product of matrices $\mathbf{U\Lambda V}^T$, where the columns of $\mathbf{U}$ and $\mathbf{V}$ are orthonormal, and $\mathbf{\Lambda}$ is a diagonal matrix of positive eigenvalues or singular values (SV) with values λ_m, $m = 1, \ldots M$. The columns of $\mathbf{V}$, $\mathbf{v}_m$, are the spatial modes, or trajectory-like pattern modes. Typically for BPM data from a transport line or a ring, the most two important modes (i.e., modes associated with the two largest SVs) are the sine-like and cosine-like trajectories. The columns of $\mathbf{U}$, $\mathbf{u}_m$, are the time patterns of each of the M trajectories (spatial modes). The length of the $\mathbf{u}_m$ is the number of sample points, P. The pair of vectors $\mathbf{u}_m$ and $\mathbf{v}_m$ is referred to as the temporal-spatial mode m. Note that the inverse of $\mathbf{B}$ is not used for anything.

The next step is to make an interpretation of the modes based on the value of their SVs or simply based on the appearance of the spatial or temporal part. Any sources of trajectory jitter (i.e., real trajectory, not readback noise) will show up as a temporal-spatial mode with a significant singular value. Because there is usually more BPMs than independent sources of trajectory jitter, the extra temporal-spatial modes represent BPM readback noise. Typically we do not know in advance how many sources of trajectory jitter there are, or equivalently, how many modes will be associated with BPM readback noise. A useful result of MIA [2] is that the SVs for the BPM readback noise modes are clustered at the bottom of the distribution of singular values. This allows the identification of the known sources of trajectory jitter and the quantification of the BPM noise for engineering purposes. If we discover more SVs above the noise floor than the expected number of independent sources, then some sources have been overlooked, and should be investigated.

SDDS TOOLKITS

It is crucial that the data in each row of the matrix $\mathbf{B}$ belong to the same physical sample (i.e., same beam pulse) otherwise the analysis will produce unclear signals. Unfortunately, the EPICS control system at APS does not guarantee that BPM data collected from different input/output controllers (IOCs) will be synchronized. Typically we use the generic SDDS monitoring tool `sddsmonitor`, which collects data from several IOCs and write them to a file. For beam pulses of repetition rate 2 Hz or lower, the data written to the file is synchronized to the same beam pulse. For the higher repetition rate of 10 Hz, such as from the APS linac, the data is not synchronized. A more sophisticated monitoring tool `sddssynchlog` was written, which internally records the EPICS time-stamp data for each monitored quantity of a given time step. If the time-stamp data for a time step fall outside a specified time spread tolerance, then the data for the sample is discarded.

We use the SDDS Toolkit for the analysis of the $\mathbf{B}$ data. Some data preparation is required, such as removing the average values and linear time trends, which is done by the polynomial fitting application `sddsmpfit`. The `sddspseudoinverse` application does the SVD decompo-

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sition and produces the **U** and **V** matrices and a list of λ_m in SDDS files. `sddspseudoinverse` can also reconstruct the data with the modes of the largest SVs specified by the user. A Tcl/Tk procedure using other toolkit applications can optionally remove BPMs from the original data after determining which ones are obviously bad or malfunctioning from a first-pass MIA analysis.

To further the MIA analysis, one can do particle trajectory simulations with the SDDS-compliant tracking code `elegant` [7] with beam jitter and BPM readback noise included. The simulated particle trajectories are analyzed the same way as the experimental data. The goal is to find the simulation parameters (e.g., the amplitudes of power supply and BPM noise) whose resulting λ_m spectrum best fit the experimental λ_m. When a match of simulation parameters is found, one has to make sure that the simulated and experimental spatial modes (**V**) are in agreement as well and have the same ordering. Any disagreement in the $\mathbf{v}_m$ indicates an incorrect model, while a difference in the ordering of the spatial modes indicates that the source amplitudes are not really a match. The use of SDDS file protocol enabled such complex integration of simulation and measurement.

APPLICATIONS

The first application of MIA at APS was the characterization of the beam jitter in the linac in June 1999 for the commissioning of the bunch compressor. The data obtained by `sddssynchlog` was used to make an obvious determination that dipole magnets that were set to zero current were the source of a strong trajectory jitter.

The next application was the characterization of the horizontal trajectory jitter in the booster-to-storage ring (BTS) transport line measured by beam position monitors (BPMs) for the purpose of improving injection efficiency. The source of the jitter was two pulsed extraction septum magnets at the start of the beamline. For the original characterization the BPMs were not yet upgraded and were very noisy. The goal was to provide the engineers with BPM noise levels and the output jitter of the septums' charging supplies. An optics model was required after MIA to calculate the actual septum output current jitter.

Only one SV dominated, with its spatial mode resembling the trajectory produced by either of the two septum magnets. Therefore, the source was ambiguous. The rms amplitude of the mode at the entrance of the storage ring (SR) was 0.67 mm. The mode was subtracted from the original data, giving only the noise. The resulting rms noise level of 0.45 mm was uniform across the BPMs. The same analysis was done for the vertical plane, which produced no trajectory jitter (as expected) and the same rms noise, which confirmed the validity of the BPM electronics noise estimate.

At a later date, the BPMs electronics were upgraded to reduce the noise level by a factor of 30. MIA was applied again in the same way to reveal a much-reduced BPM noise level of 0.025 mm. Figure 1 shows the reduced noise level after the BPMs were upgraded, and Figure 2 shows the corresponding reduction in SV spectrum.

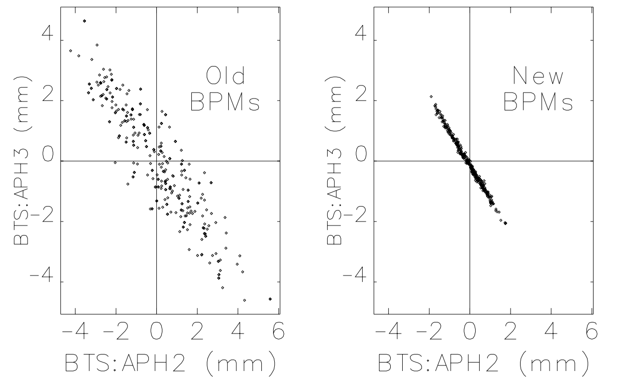

Figure 1: Correlation between two BTS BPMs showing change in electrical noise after upgrade.

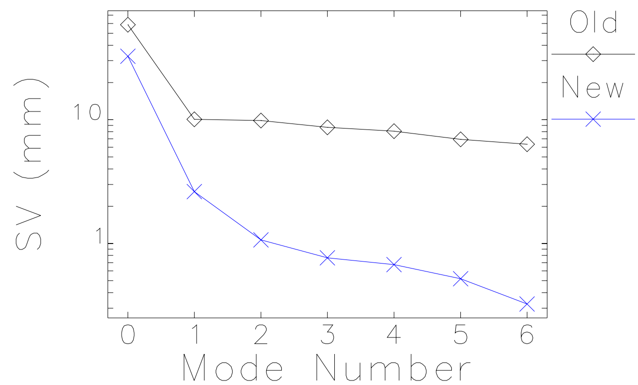

Figure 2: Comparison of SV spectrum after the BPM upgrade.

MIA revealed three modes instead of one. The strongest mode was the same as before, and two new modes appeared clearly above the noise floor. The second spatial mode originated because the two septums are independent and can create a cosine-like trajectory pattern to complement the sine-like trajectory of a single-septum angle error. The third spatial mode is an energy jitter that is caused by the booster dipole ramping supply. The correct identification of these two new spatial modes was confirmed by tracking simulations. Actually, the two spatial patterns don't look like the pure cosine-like trajectory or dispersion trajectory because these trajectories are necessarily orthogonal to the main angle trajectory, forcing a certain mixing of the pure physical trajectories.

The same number of data points were used in the MIA analyses that produced the spectra of Figure 2, which allowed the direct comparison of the spectra. If the septum noise was unchanged, then we would expect the largest SV in each curve to be equal. However, it appears that the septum noise was reduced by almost a factor of two. It is possible that in the two years between measurements that improvements were made to the septum.

The SVs of the experimental data (λ_m^{exp}) for the three modes can be fitted to those of a beamline model. The main parameters of the model were the amplitudes of the septum relative strength errors, which were scanned over a 10x10 grid. The grid calculation was repeated for a few values of energy jitter. For simplicity, a uniform distribution of error was adopted, which is probably more realistic for power supply regulation and energy jitter. The BPM noise amplitude was fixed at 0.050 mm for the simulations, which closely reproduced the observed rms of 0.025 mm. We already had an idea of what the energy jitter would be due to the booster ramp data. Measurements of the 360-Hz ripple produces a relative dipole current error of typically 10^{-4} at the extraction time. The SVs calculated for each simulation (λ_m^{sim}) were written to an SDDS file, which facilitated calculating the quantity $\Delta = \sum_m^3 \left(\lambda_m^{\mathrm{exp}} - \lambda_m^{\mathrm{sim}}\right)^2$ for each simulation. One such set of Δ is displayed in a contour plot in Figure 3. In this particular contour plot, there may be more than one solution. At the very least one can conclude that both septums contributed to the jitter of the trajectory.

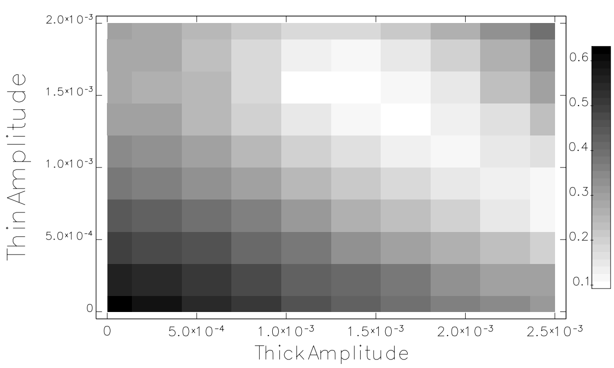

Figure 3: Contours of the differences of the experimental and simulated SVs.

We also analyzed the BTS trajectory noise with all quadrupole magnets turned off. Since the trajectory sources do not change, we expected the same solution for the septum noise amplitude from a different contour plot of Δ . Because the beam size eventually grew to the dimension of the beam pipe, most of the BPMs stopped functioning normally, which made the use of a model simulation difficult.

Also, we temporarily installed a different (lower noise) pulsed supply for the thin septum. We did this at a time when only two new low-noise BPMs had been installed in the BTS. Unfortunately the new and old BPMs have different timing systems and are not synchronized in general (`sddssynchlog` wouldn't have helped), so they could not be used together in MIA. We attempted to do MIA with two new BPMs only and with the five old BPMs only with two sets of data (one with the old supply and another one with the new supply). The spatial modes do not change with the supply, but the SVs are reduced by about 10% with the new supply, suggesting that the new supply really had reduced jitter. In May of 2003, the booster extraction septums will have improved charging supplies, and MIA will be able to quantify the improvement.

We extended the problem to analyzing the BTS trajectory plus the SR trajectory using the single-pass capability of the SR BPM system. The analysis is expected to produce the additional trajectory noise contributed by the two SR injection septum magnets. There will be five sources of noise in all. We had to remove the bad SR BPMs using a threshold criterion on the elements of $\mathbf{V}$, and repeat the MIA analysis with the bad BPMs removed. The strongest mode was the combination of the original strongest BTS spatial mode plus an oscillatory trajectory throughout the whole SR. It was expected that the SV spectrum would have five SVs standing out. However, as Figure 4 shows, there is one dominant mode, but the other SVs do not stand out clearly even though the spatial patterns have reasonable trajectories. We have not yet done `elegant` simulations of the trajectory. It is hoped that the modes will be better understood through a comparison with simulations.

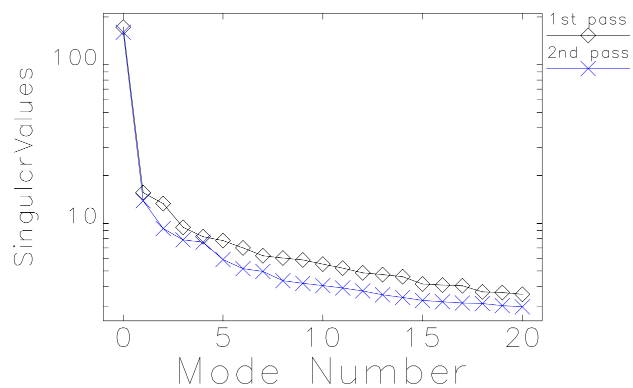

Figure 4: Part of spectrum of SVs for combined BTS-SR beamline before and after removing bad BPMs.

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