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LOCO CORRECTIONS FOR BEAM TRAJECTORY OPTIMISATION ON THE ISIS ACCELERATOR

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Abstract

The ISIS facility at the Rutherford Appleton Laboratory, UK, produces neutron and muon beams for condensed matter research. Its 50 Hz, 800 MeV proton synchrotron delivers a mean beam power of 0.2 MW to two tungsten spallation targets.

The beam optics correction technique implemented in this work is Linear Optics from Closed Orbits (LOCO). LOCO modifies existing accelerator models according to a measured orbit-response matrix (ORM). This correction technique identifies imperfections in the machine lattice, and discrepancies between the machine and model.

The identification of erroneous elements through analysis of the measured ORM is demonstrated in this paper. In comparison to the operational settings achieved through the existing correction techniques, the initial test of the LOCO code demonstrates a 17 % improvement to the RMS trajectory deviation in the horizontal plane. It also shows an 11 % horizontal and 30 % vertical decrease to the standard deviation of trajectory measurements.

INTRODUCTION

The ISIS synchrotron accelerates pulses of 3×10^{13} protons from 70 MeV to 800 MeV at 50 Hz. Particles orbit the ring 12,000 times in the 10 ms acceleration cycle. The 163 m circumference ring contains 32 beam position monitors (BPMs), 14 steering magnets and 20 trim quadrupoles, to measure and adjust the beam optics. Errors in the lattice can result in deviations from the optimal orbit which are difficult to correct empirically. In order to minimise beam loss while maximising beam intensity and use of the available aperture, it is vital to be able to accurately manipulate the beam dynamics throughout the machine.

The Linear Optics from Closed Orbits (LOCO [1]) correction technique, implemented successfully on accelerators worldwide (Fermilab and CERN Boosters [2], Swiss Light Source (SLS) [3]), monitors the behaviour of the beam due to magnet perturbations in an orbit-response matrix (ORM). It then fits perturbations in a simulated version of the ORM, created using existing models in the accelerator design software MAD-X [4] to the measurements. After successful fitting, the resulting matrix is an accurate representation of the machine performance. The modifications made to the model are then reversed and implemented on the machine in order to locate and counteract errors identified by the fitting procedure.

EXISTING CORRECTION PROCEDURE

A model of the accelerator was created in order to predict and study beam optics throughout the machine. This provides the ability to build up a matrix of the ideal responses of all magnets throughout the acceleration cycle.

Originally, the correction technique used was based on the linear equation

$$x_i=R_{ij}\theta_j$$

where x_i is the measured position at monitor *i,* R_{ij} is the element in the response matrix and θ_j is the kick to magnet *j*. The matrix was minimised through Singular Value Decomposition in order to determine solutions for θ_j [5].

Later the model was rewritten in MAD-X and its orbit correction capabilities exploited. These corrections directly take measured positions from the machine and vary the N most efficient steering magnets in the model to fit this trajectory. The opposite changes can then be applied to the machine to centre the beam [6].

Though a measured ORM was recorded to aid with steering magnet strength calibration, the MAD-X model and subsequent calculations do not include the ORM in calculations and is therefore not a perfect correction. The constant evolution of real errors on the machine reduces the effectiveness of this method. By measuring a response matrix on the machine and using this in the calculations, the locations of alignment and field errors can be acknowledged and minimised in the correction. Another advantage to the LOCO method is that it uses only response measurements and magnet settings in calculations to determine adjustments to operational magnet settings.

ORBIT-RESPONSE MATRIX

The LOCO method relies on the measurement of the ORM. This is measured by recording the beam position response on the same pulse at all BPMs for a change in current applied to each individual magnet. Each element in the matrix is formed by taking the gradient of three points measured in this fashion. In order to accurately represent the real machine dynamics, the statistical error taken at the 95% confidence level is included in calculations.

The ORM measurements begin with the machine operational setup with a reasonably well-centred beam. The initial measurements from the BPMs are recorded before magnets are individually varied twice, in turn. On each current change, the beam loss was checked around the ring to ensure the beam remained in the vacuum chamber.

During these measurements, it is important to ensure that the current adjustments are large enough to record a measurable change at the BPMs, but small enough that the beam remains within the vacuum chamber. Therefore, the choice of measurement timing and kick strength are important factors. Measurements at ISIS are taken at 4 ms in the acceleration cycle with a total current range of 40 A per magnet. This allows a balance between available aperture and magnetic rigidity.

Since the measured ORM relates to a specific setup of the machine, the response matrix should be re-measured

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before each correction attempt. Measuring a 1,088-element ORM for the entire synchrotron takes roughly 3 hours so is a viable option for a setup shift. Due to the design of the monitors in the High Energy Drift Space (HEDS) at injection, measuring an equivalent 132-element ORM takes 16 hours and is therefore not reasonable for correction shifts.

The existing MAD-X model has been modified to extract the Twiss parameters for orbit response calculations at a monitor (x_i) due to the kick at a magnet (θ_j):

$$\frac{\Delta x_i}{\Delta \theta_j}=\frac{\sqrt{\beta_i\beta_j}}{2\,sin(\pi\nu_x)}\,cos(|\psi_i\text{-}\psi_j|\text{-}\pi\nu_x)$$

where $\beta_{i,j}$ is the beta function and $\psi_{i,j}$ is the phase at the monitor or magnet respectively, and ν_x is the horizontal betatron tune [2]. By individually simulating a change in all variable parameters (currents, misalignments and tilts), the ORM is built up similarly to the machine measurements.

New calibration values for conversion between dipole current and kick strength were calculated from the ORM data for each individual magnet, to improve the balance between variables and constraints over.

For comparison, the operational model and measured response elements are plotted against each other in Fig.1, where a slope of 1 indicates a perfect agreement.

All linear best fits in Fig. 1, lie within 0.1 mm/A below ideal agreement, indicating that the model expects larger responses. This may be a consequence of magnet field errors, systematic BPM calibration errors or the model itself.

The measurements indicate an RMS error of 0.2 mm, suggesting good agreement between model and machine.

The largest discrepancy originates from the measurements for the steering magnet R5HD1, shown in light blue in Fig. 1. The deviations are most prevalent in monitors directly after the magnet and only in the same-plane measurements. Further investigation revealed a discrepancy in the azimuthal location of the magnet. The model had defined R5HD1 ~5 m later than its actual location on the machine.

The response matrix shows negligible coupling in magnet behaviours, so the choice was made to use only same-plane magnets to correct for horizontal and vertical errors.

LOCO CODE

The existing model is written in MAD-X and returns the Twiss parameters at all elements. A Python script was written to collect these data and create an ORM with 147,968 elements (1,088 elements for each variable parameter).

The measured ORM is loaded into a vector and the artificial ORM is loaded into a matrix where each column is an ORM measured for a varied parameter.

During this development stage, Microsoft Excel was used as a front-end to the code, providing a readily accessible version of the measured and calculated ORMs, and the measurements taken to create them. Future work could create a LabVIEW interface for integration with existing beam physics software.

An error vector (equivalent to the chi^2) is calculated and minimised via Singular Value Decomposition to create the modifications needed to represent the real machine dynamics. This is an iterative fitting procedure as not all errors are linear with respect to the magnetic fields.

The modifications made to the artificial ORM are reversed and implemented on the machine.

When the LOCO code was tested on operational beam pulses, the code completed in under 10 seconds and was shown to converge to final values in 3 iterations, shown in Fig. 2.

The minimisation in this technique is under-constrained, as more monitors are used than relevant-plane magnets. The choice of singular values in the fitting is therefore important. Too few singular values will create changes which are too small to be implemented, and too many will produce changes too large for the magnets to manage. The Python code automatically selects the number of singular values to use and has used six in the fitting in Fig. 2.

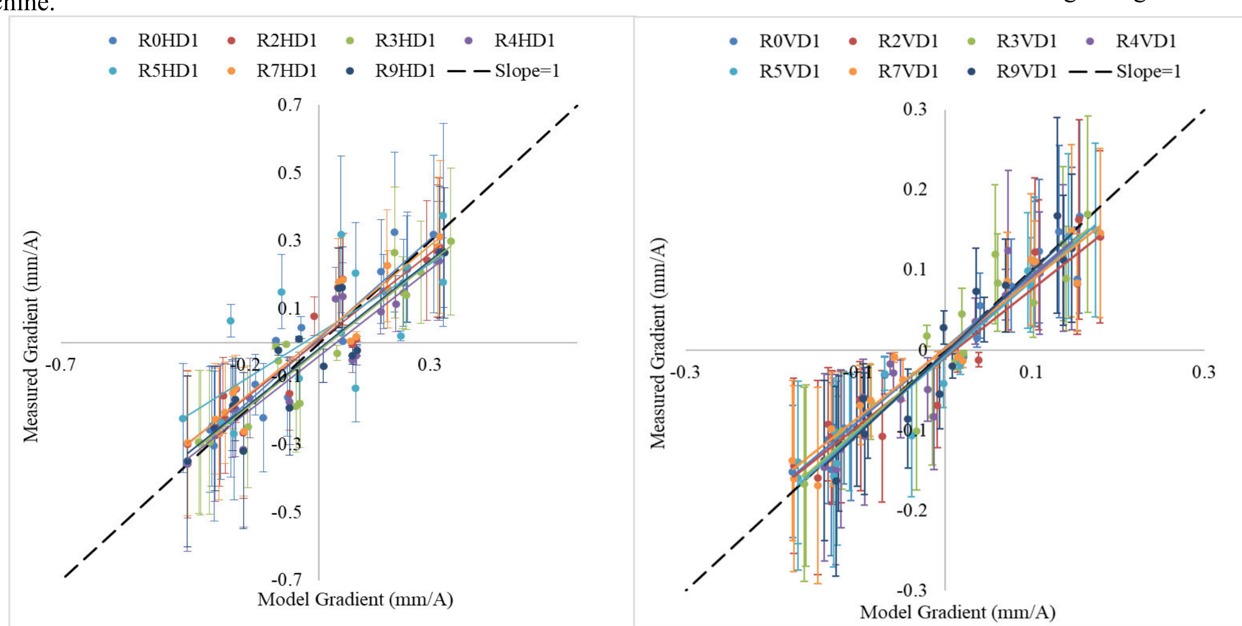

Figure 1: Model and measured matrix elements for comparison for horizontal dipoles (HD) and vertical dipoles (VD).

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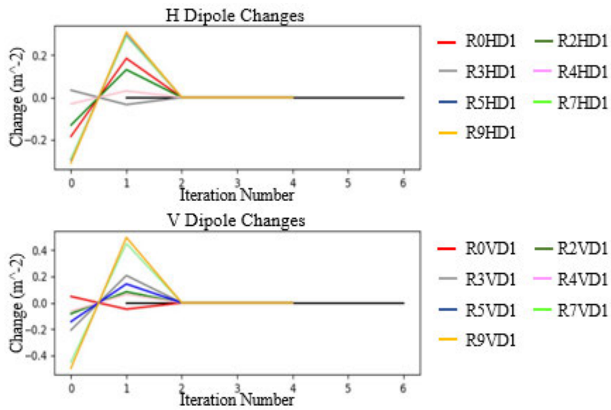

Figure 2: Current changes converge within 3 iterations during iterative fitting procedure.

CORRECTIONS

After collecting the magnet settings from the operational machine, already treated via the existing correction technique, a LOCO correction was attempted on the machine and the results are shown against the operational positions in Fig. 3.

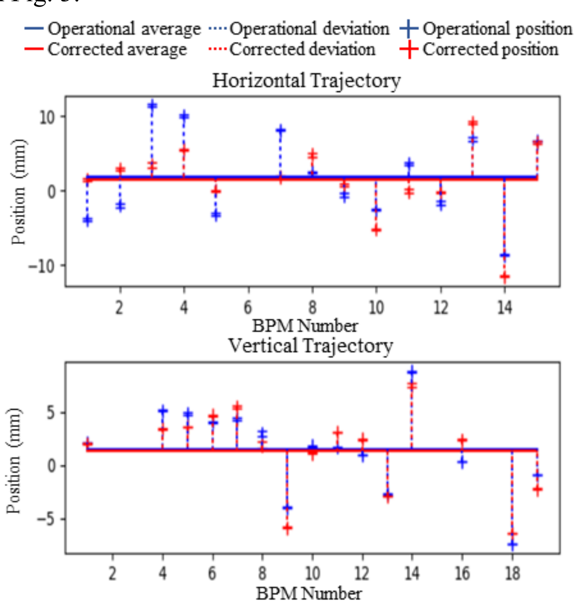

Figure 3: Operational trajectory and trajectory after basic correction plotted for comparison

From the operational average position, the uncorrected RMS deviations were 6.13 mm and 4.19 mm in the horizontal and vertical planes respectively, with pulse-to-pulse standard deviations of 0.23 mm and 0.12 mm. These standard deviations indicate a stable beam, allowing for repeatable measurements.

After the LOCO code had run, the results were implemented on the machine. The misalignment errors indicated fell well within acceptable limits (set to 0.5 mm) in both planes and beam loss remained reasonable. The horizontal RMS deviations reduced to 5.12 mm with a standard deviation of 0.17 mm. The vertical RMS deviations showed negligible change at 4.11 mm, but standard deviation was improved to 0.07 mm.

The LOCO code succeeded in smoothing the trajectory of the beam horizontally by 17 % whilst retaining the vertical RMS value which was already well-centred and improved the standard deviations at 4 ms by 11 % and 30 % horizontally and vertically respectively, making an improvement to the level of stability reached by operational techniques. This was also achieved with reduced steering magnet currents which is beneficial for power consumption and equipment lifetime.

CONCLUSIONS

The LOCO method builds on the correction technique currently used for beam optics correction on the ISIS accelerator. Through the inclusion of real machine errors, the calculations produce an improvement to beam trajectory fluctuations and the stability of the machine, in comparison to the current technique. This correction is limited by the compactness of the ring and the ability to adjust individual magnets. The minimisation is under-constrained as there are more monitors than magnets, so careful consideration should be given to the choice of elements included. The main magnets in the synchrotron are not individually adjustable and therefore cannot be included in this technique.

The machine matches the ideal model very well, revealing few large errors in the machine. Small errors were corrected with respect to their effects on beam position and indicate that the method is a positive contribution to machine tuning and can also be used as a diagnostic tool to monitor element degradation or adjustments.

Further work to include beam envelope and tune corrections can be incorporated, extending the effect of the measured ORM in setup shifts. Measurements have been taken to include quadrupole corrections in the code and can be included in these future correction attempts.

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