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TOWARDS AN ADAPTIVE ORBIT-RESPONSE-MATRIX MODEL FOR TWISS-PARAMETER DIAGNOSTICS AND ORBIT CORRECTION AT DELTA

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Abstract

At DELTA, a 1.5-GeV electron storage ring operated by the TU Dortmund University, preliminary tests of an adaptive orbit-response-matrix model were conducted. Closed orbit perturbations corrected by the slow orbit feedback can be buffered and used to update a fit of the bilinear-exponential model with dispersion (BE+d model). This model is a representation of the orbit-response matrix depending on the beta functions, the betatron phases and the tunes in both planes. This work introduces a new fitting recipe to obtain good estimates of the aforementioned quantities and evaluates a BE+d-model represented orbit-response matrix for orbit correction. Numerical studies are shown along with measurement results.

A NEW BEAM-STEERING AND DIAGNOSTICS TOOL

A new slow-orbit-feedback software [1] is under development at DELTA, a 1.5-GeV synchrotron radiation light source operated by the TU Dortmund University. Based on the bilinear-exponential model with dispersion (BE+d model) [2], this work explores integrating the new software with an adaptive orbit-response-matrix model for recovering optical functions according to the ideas presented in [3] and maintaining a well working orbit-response matrix to estimate orbit correction steps when switching beam optics.

The storage ring at DELTA is equipped with $J = 54$ capacitive beam-position monitors (BPMs) to measure the transverse beam position in $W = 2$ planes [4]. The majority of read-out electronics are Bergoz MX BPMs [5]. Their resolution is limited by the CAN-BUS modules digitizing the measurement signal to about 4.9 µm (12 bit for ±10 mm). The remaining BPMs are equipped with Libera Electron and Libera Brilliance read-out electronics which achieve a resolution of <5 µm for typical beam currents [6].

For beam steering, 30 horizontal and 26 vertical steering magnets, $K = 56$ in total, are available [7]. The maximum deflection angles are up to 3.13 mrad for horizontal steering magnets and 1.13 mrad for vertical steering magnets.

The new slow-orbit-feedback software applies global correction steps with a maximum rate of about 0.1 Hz [1]. The basic idea for integrating the adaptive orbit-response-matrix model is to store the corrected orbit displacements $\Delta\vec{\kappa}$ ($W \cdot J$ elements) and the applied changes in steering angles $\Delta\vec{\theta}$ (K elements) in a ring buffer of length N while a subprocess continuously updates the BE+d model on this buffer.

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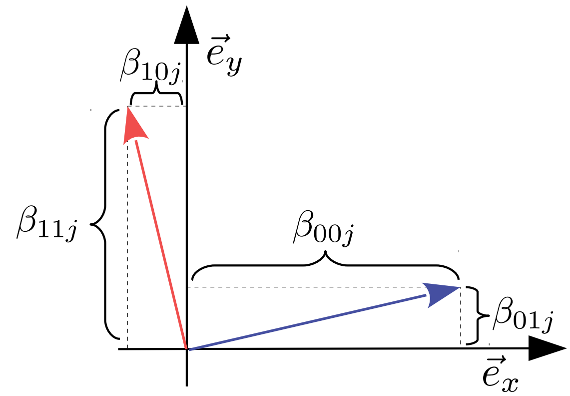

Figure 1: Beta function values β_{mwj} of coupled betatron oscillations at BPM j. The first mode ($m = 0$) is mostly horizontal. The second mode ($m = 1$) is mostly vertical.

THE BILINEAR-EXPONENTIAL MODEL WITH DISPERSION (BE+D MODEL)

According to the BE+d model [2], the orbit displacement $\Delta\kappa_{wj}$ at BPM j in plane w divided by the steering angle $\Delta\theta_k$ at steering magnet k

$$\frac{\Delta\kappa_{wj}}{\Delta\theta_k} = \sum_{m=0}^{M-1} \Re\left\{Z_{mwj}A^*_{mk}e^{-i\pi q_m S_{jk}}\right\} + d_{wj}b_k,$$

is determined by the sum over $M = 2$ modes of betatron motion and dispersion. The plane index w refers to either the horizontal or the vertical plane. The separation of the indices m and w incorporates coupled betatron oscillations into the model. These are not confined to a single plane. For this reason, the phasor

$$Z_{mwj} = \sqrt{I_m\beta_{mwj}}e^{i\Phi_{mwj}}$$

is indexed with both m and w. It encodes the amplitude and phase of the betatron oscillation of the m-th mode where β_{mwj} is the projection of the beta function into the w-th plane at BPM j (Fig. 1) and Φ_{mwj} is the corresponding betatron phase. The invariant of motion I_m is proportional to the Courant-Snyder invariant [3].

The remaining model parameters are the tune of the m-th mode q_m, the factor S_{jk}, which is either -1 if the k-th steering magnet is downstream of the j-th BPM or 1 otherwise, an unnormalized dispersion d_{wj}, which is related to the dispersion function by an unknown factor, the corrector parameters A_{mk} and the dispersion coefficients b_k.

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For a measured orbit-response matrix $\mathbf{R}_{\text{meas}}$, the matrix $\mathbf{R} = (R_{wjk})$ which minimizes $\|\mathbf{R}_{\text{meas}} - \mathbf{R}\|^2$ is its BE+d-model representation. Here, R_{wjk} is the response matrix element according to the BE+d model and $\|...\|$ is the Frobenius norm.

Closed-Orbit Bilinear-Exponential Analysis

The closed-orbit bilinear-exponential analysis (COBEA) algorithm is available to determine the BE+d-model representation of a given orbit-response matrix by decomposing it into beta functions β_{mwj}, betatron phases Φ_{mj} and tunes q_m at all BPMs [3]. An unnormalized dispersion function d_{wj} is also calculated [8].

As additional input, COBEA only requires the ordering of BPMs and steering magnets along the beam path to determine the factor S_{jk} and the length of a drift space enclosed by two BPMs to calculate the invariants of motion I_m of both modes.

A NEW FITTING RECIPE

Fitting the BE+d model on a buffer of length N requires minimizing the objective function

$$f = \sum_{n=0}^{N-1} \left|\Delta\vec{\kappa}_n - \mathbf{R} \cdot \Delta\vec{\theta}_n\right|^2 .$$

Solving this optimization problem with random start values only converges in a small fraction of cases. COBEA's method of generating start values, however, cannot be directly applied to the buffer because it explicitly requires orbit-response matrix elements as input. Generating these with a linear regression from the buffer discards a major advantage of the BE+d model. Compared to the orbit-response matrix, which has

$$W \cdot J \cdot K = 6048$$

degrees of freedom, the model only has [2]

$$(2M + 1)(WJ + K) - M - 1 = 817.$$

A direct fit of the BE+d model should therefore achieve better results than COBEA via the detour of a linear regression on small buffers. Thus, a new fitting approach was investigated.

The degrees of freedom of the fitted model $\mathbf{R}$ were increased in three steps while using the results of the previous step as start values for the next step. The start values for the first step were random except for the tunes.

The complete optimization recipe then consists of the following three steps:

1. Fit decoupled BE+d model with a single mode ($M = 1$) and without dispersion in both planes separately (166 degrees of freedom in the horizontal plane and 158 degrees of freedom in the vertical plane).

2. Fit complete BE+d model but vertical constant tunes (815 degrees of freedom).

3. Fit complete BE+d model including tunes (817 degrees of freedom).

The idea for this approach is based on inter-plane coupling and dispersion having only small effects on the overall calculation outcome.

All three steps were implemented in the Python programming language with the tensorflow package [9] using the Adam optimization method [10]. This optimization method is an evolution of stochastic gradient descent that leverages momentum to scale local minima and utilizes feature-specific learning rates to accelerate convergence.

Buffer and start values for the tunes aside, the introduced fitting recipe requires the same additional input as COBEA (ordering of BPMs and steering magnets along the beam path and length of a BPM-enclosed drift space) and produces the same output: beta function values, betatron phases, fitted tunes and an unnormalized dispersion.

Verification

A set of 250 orbit displacements $\Delta\vec{\kappa}$ was measured by randomly applying steering angles $\Delta\vec{\theta}$ at the storage ring at DELTA. About 30 steering magnets (includes both planes) were used on average per measurement. The average steering angle per steerer was 0.02 mrad (average included only used steering magnets). The average maximum orbit displacement was 530 µm. Tunes were measured before and after applying the steering angles using the kicker-based tune measurement of the storage ring [11]. BPM 12, BPM 33 and BPM 45 were removed in post processing of the collected samples. BPM 12 and BPM 45 had known hardware issues. BPM 33 produced spurious results in fitted betatron phases in both planes.

The introduced fitting recipe was tested on the measured samples multiple times in two different setups. The resulting averages for the horizontal betatron phase (Fig. 2), the horizontal beta function (Fig. 3), the vertical beta function (Fig. 4) and the vertical tune (Fig. 5) for each setup were

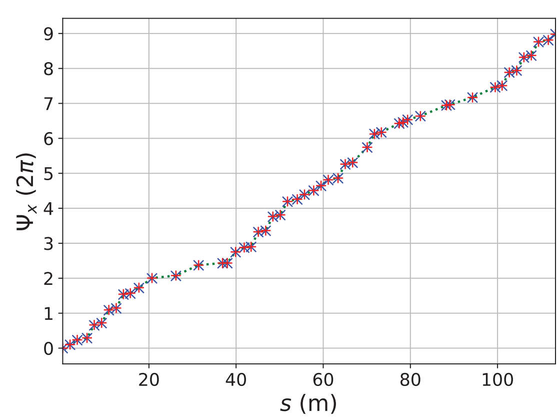

Figure 2: Comparison of average horizontal betatron phase advances at BPMs for fits over complete set of measurements (blue) and fits over sets of 45 randomly chosen samples (red) with COBEA results (green) as reference.

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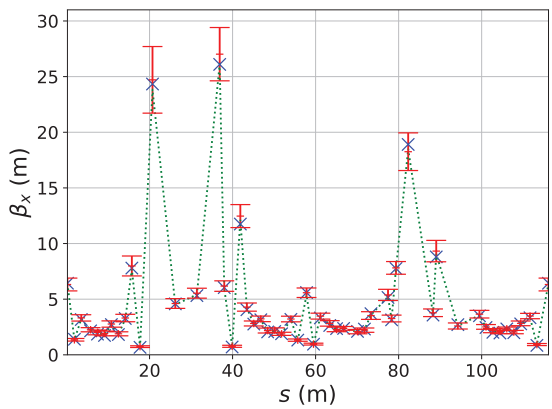

Figure 3: Comparison of average horizontal beta function at BPMs for fits over complete set of measurements (blue) and fits over sets of 45 randomly chosen samples (red) with COBEA results (green) as reference.

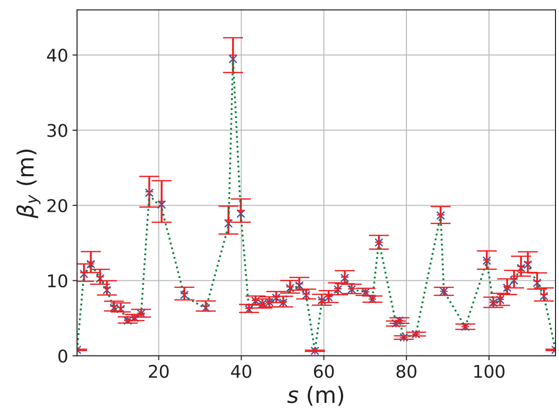

Figure 4: Comparison of average vertical beta function at BPMs for fits over complete set of measurements (blue) and fits over sets of 45 randomly chosen samples (red) with COBEA results (green) as reference.

compared to COBEA results (green). Here, horizontal beta function means the spatial projection of the beta function of the first mode ($m = 0$) onto the horizontal axis (Fig. 1). The same holds true for the vertical beta function with the second mode ($m = 1$) and vertical axis. The COBEA results were generated by decomposing an orbit-response fit over the complete set of 250 samples with COBEA. That is roughly five times the required amount of the $K = 56$ linearly independent samples to achieve a unique fit and was deemed sufficient to achieve a good fit.

In the first setup, the robustness of the introduced fitting recipe was determined by applying it on the complete set of 250 samples. This process was repeated 100 times with different random start values to aggregate convergence statistics. The average runtime was about 150 s on a standard desktop computer. The average fitted horizontal and vertical tunes missed COBEA tunes by 0.4 % and 0.2 % but were still very close (blue, Fig. 5). The resulting averages for beta function values in both planes (blue, Fig. 3 and Fig. 4) and betatron phase (blue, Fig. 2) practically coincided with COBEA results (green). Standard deviations for the calculated beta function values, betatron phases and tunes were so small that they were omitted. This confirms the introduced fitting recipe to converge independent of start values and therefore robustly fit the BE+d model.

In the second setup, it was investigated whether the introduced fitting recipe performs well on small buffer sizes by applying it to 300 sets of 45 randomly selected samples. Due to the small set sizes and therefore strong noise levels in the data, 10 % of fits diverged. Fits were ruled out as diverged when the projection of beta functions of the horizontal mode into the vertical plane exceeded 5 m and vice versa (decoupled machine assumption). Diverged fits were excluded from analysis. All remaining fits converged to nearly the same betatron phases which coincided with COBEA predictions (red, Fig. 2). Standard deviations for betatron phases were therefore omitted. Beta function values and tunes deferred from fit to fit. The average fitted horizontal and vertical tunes missed COBEA tunes by 2.6 % and 0.7 % and fluctuated considerably (red, Fig. 5). The average beta function values matched COBEA results well (red, Fig. 3 and Fig. 4). Even when considering standard deviations, the fitted beta function values in both planes replicated all pronounced features of the COBEA reference. Prime example of this are the two maxima of >20 m around the U250 undulator in the first half of the storage ring. Considering the fact that COBEA can only be used with buffer sizes of $K = 56$ and above, these results assert the alleged capability of the new fitting recipe to surpass COBEA on small buffer sizes.

The BE+d model is based on linear beam dynamics where orbit displacements caused by changing steering strengths should not be accompanied by tune shifts. The distribution of vertical tunes (Fig. 5) indicates that this assumption does not hold for the conducted measurements. Neither the fitted tunes produced with the new fitting recipe nor COBEA results matched the vertical mean tune (orange) well. The tunes fitted in the second test setup even missed the standard deviation of the tune distribution. In consequence, Investigating whether skipping the final step of the fitting recipe and keeping the tunes fix at mean tunes yields any benefits regarding the stability of the fitted beta function values and betatron phases seems promising.

MODEL-BASED ORBIT STEERING

Betatron motion and orbit response in an accelerator are mostly determined by quadrupole field strengths. The capability of an orbit feedback relying on a measured orbit-response matrix to estimate correction steps therefore deteriorates when quadrupole currents are changed. Utilizing a continuously updated BE+d-model representation of an orbit-response matrix instead could compensate this problem. Its few degrees of freedom make the model suited to adapt to changing beam optics fast. However, first it needs to be established that the BE+d model representation of a mea-

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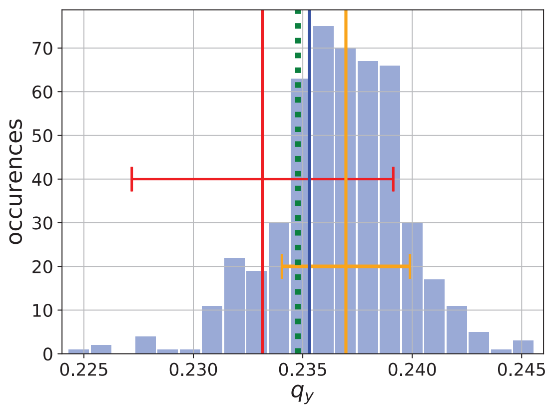

Figure 5: Comparison of the average vertical tunes determined by fits over the complete set of measurements (blue) and fits over sets of 45 randomly chosen samples (red) relative to the distribution of vertical tunes across all measurements (light blue bars). The distribution mean (orange) and COBEA results (green) are given as reference.

sured orbit-response matrix can be used for orbit correction at all.

Proof of Principle

The BE+d model was tested for orbit correction by randomly disturbing the orbit of the storage ring at DELTA and using either a measured orbit-response matrix or its COBEA-fitted BE+d-model representation for matrix-based orbit correction. The benchmark for this comparison was the weighted distance

$$\chi_h = |\mathbf{W} \cdot (\vec{\kappa} - \vec{\kappa}_{\mathrm{ref}})|$$

in between measured orbit $\vec{\kappa}$ and orbit reference $\vec{\kappa}_{\mathrm{ref}}$ in the horizontal plane which is the standard benchmark for orbit-correction quality at DELTA [1]. Here, $\mathbf{W}$ is a real-valued diagonal weight matrix. The difference of this distance $\Delta\chi_h$ before and after orbit correction determines whether an orbit-correction step was successful. A negative result indicates better matching of orbit and orbit reference and therefore a success. Correction steps were iteratively repeated until χ_h was minimized below a threshold. About 500 correction steps each were made for a set of two measured matrices routinely used in user operation and their model representations. The distribution of $\Delta\chi_h$ is displayed in Figure 6 for the measured response matrices (blue) and their BE+d-model representations (red).

The distribution is very similar for both the measured orbit-response matrices and their BE+d-model representations. The number of miscorrections for the BE+d-model of about 7 % was close to the 8 % miscorrections achieved with the measured matrices. The average decrease $\Delta\chi_h$ was not significantly better for the BE+d-model representations (red line) compared to the measured matrices (black line). All in all, the measured matrices and their BE+d-model representations work equally well for orbit correction.

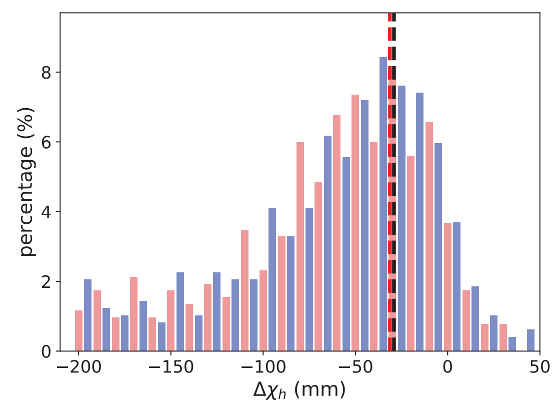

Figure 6: Distribution of $\Delta\chi_h$ for orbit-correction steps made with two measured orbit-response matrices (blue bars, mean: black line) and their BE+d-model representations (red bars, mean: red line).

CONCLUSION & OUTLOOK

The idea of integrating the bilinear-exponential model with dispersion (BE+d model) into the new slow-orbit-feedback software at DELTA was investigated. This setup aims at non-invasively obtaining good estimates for beta functions and betatron phases in both planes and providing an adaptive orbit-response matrix for estimating correction steps. A new fitting procedure was introduced to fit the BE+d model directly on a ring buffer and was compared to results of the closed-orbit bilinear-exponential analysis (COBEA) algorithm based on a linear regression on the ring buffer. The new fitting procedure yielded results on par with COBEA results for large buffers and achieved acceptable results on small buffers where the orbit-response fit required to use COBEA was underconstrained. Finally, the viability of using a BE+d-model representation of a measured orbit-response matrix for orbit correction was asserted by benchmarking two measured matrices against their BE+d-model representations with the new slow-orbit-feedback software under development.

The utilization of a BE+d-model-based live-updated adaptive orbit-response matrix for non-invasively measuring optical functions and orbit correction will be further investigated. First, the dispersion output of the introduced fitting recipe needs to be validated. Also, it will be investigated whether skipping the third step in the introduced fitting recipe yields better estimates for beta function values and betatron phases. Further research should target determining a suitable length for the ring buffer. Finally, first orbit-correction tests with a live-updated BE+d model should be considered.

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