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Finding Beam Focus Errors Automatically*

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The Problem

Mathematical models are powerful tools for designing beam-lines. In principle, once a beam-line has been constructed, the models should also be useful in reducing the time to find errors in the beam-line. However, as discussed in the examples below, the model is usually not initially a satisfactory representation of the physical beam-line and thus cannot be used to locate or correct errors. In this paper we present techniques that use models to find errors in beam-lines. We also give examples where these techniques have been used successfully. The techniques significantly reduced the costly time needed to find beam-line errors.

The use of mathematical models in the control of accelerators, storage rings, and beam lines started with the computer control of SPEAR During the commissioning of SPEAR, it was found that the machine functions as predicted by the model did not agree with the measured values. Experiments were done to measure the machine tunes for many configurations with different values of β and η at the interaction point, β^* and η^*. These data were used to calculate "correction factors" which modified the value of the quadrupole magnet strengths so as to minimize the discrepancies between the model and measured machine tune values. These correction factors are too large to represent any conceivable physical cause but must be used in any mathematical modeling of SPEAR.

The same problem occurred during the commssioning of PEP several years later. Since PEP was designed to run with configurations having fixed β^* and η^*

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values, it was not possible to use the above method to calculate the correction factors for PEP. Instead, the correction factors were calculated by fitting the model predicted value of the transfer matrix element, C_{ij}, to the measured value. Here, C_{ij} is the change in the closed orbit trajectory at the i^{th} monitor per kick θ_j from the j^{th} corrector, namely $C_{ij} = Dx_i/\theta_j$. In our notation the first index on a transfer matrix refers to the monitor and the second index refers to the corrector. Unfortunately, the errors in the measured beam position data were so large that this scheme did not give reliable results.

The same machine function problem occurred again in 1983 during the commissioning of the South Damping Ring (SDR) of the SLC. After many weeks of manually knobbing the strength of every quadrupole magnet, beam was finally stored. In this empirically "knobbed" configuration, the tune values as well as the value of the β and η functions were found to be quite different from the model prediction. Because of this discrepancy, it was impossible to set up the machine to its design configuration using the model. However, the SDR beam position measurements were sufficiently accurate to permit a solution using the C_{ij} fitting scheme mentioned above.

Many tests were made with this program[1] and after several weeks a -3% error was discovered in the defocussing quadrupole magnet strength. The initial commissioning of the SDR was completed once the calibration of the quadrupole magnet strength was changed.[5] Using this new model the machine lattice parameters could be set to their design values. Futhermore, the ring parameters could be varied in a predictable way to systematically study their effects on the beam. Based on the results of these studies, the North Damping Ring (NDR) was redesigned.[6]

A somewhat different situation was encountered during the commissioning of the NDR. For several weeks, no beam could be stored. Without a stored beam a closed orbit could not be measured and thus C_{ij} could not be determined. But, from the first turn trajectory the value of T_{ij} was measured and was used instead of C_{ij}. T_{ij} is the change in the trajectory at the i^{th} monitor per unit kick from the j^{th} corrector, $T_{ij} = Dx_i/\theta_j$. After about a week of measurement and calculation, two correction factors were discovered: one for QF (1.04) and one for QD (1.04), where QF and QD are the focussing and defocussing quadrupole magnets in the cells of the ring. With these correction factors in the model, allowed beam to be stored immediately. The NDR is now under routine operation using this model.

The Manual Solution

Up to now, the scheme used to find these correction factors was performed manually by a trial-and-error, time-consuming method. An outline is described below:

1. Adjust the model by introducting a trial strength error into a particular quadrupole family.
2. For each error, calculate from the model the T_{ij} for a specific j^{th} corrector.
3. Compare the result from step 2 with the measured result.
4. Repeat steps 1 to 3 for different trial values of strength error to find the "best fit" solution to the beam data.
5. Repeat steps 1 to 4 for another quadrupole family.
6. Repeat steps 1 to 5 for the other beam plane.

Using this scheme, it took about three weeks to find the error in the South Ring and about one week to find the error in the North Ring. Fortunately, the errors in both cases were in a family of magnets and not in the strength of an individual magnet. Otherwise, this manual scheme would have been too clumsy and tedious to be useful. Since this problem has occurred so frequently, we decided to automate the scheme.

The Automated Solution

An automated method[4] was developed using a state-ot-the-art non-linear optimization program, NPSOL.[5] NPSOL is extremely powerful since it can be used to find a solution subject to constraint conditions, a feature up to now unavailable in other optimization programs. NPSOL is used to find family strength errors (correction factors) and individual magnet strength errors. The program does this by minimizing the difference between the model predicted C_{ij} or T_{ij} values. (For the case of C_{ij} fitting, it is possible to impose the optional requirement that the model predicted tunes equal the measured tunes.)

The program to find these errors is an extension of COMFORT[6] called COMFORT-PLUS. The steps involved in finding the correction factors using COMFORT-PLUS are illustrated in the next section.

Error Simulation and Program Test

In order to evaluate the usefulness of COMFORT-PLUS, we took the NDR as an example. Many test cases were studied. In each test case, the strength of the quadrupole magnets in the COMFORT data set were changed manually from their design values to simulate errors as would occur in a real machine. This dataset was used to calculate a change in the first turn trajectory per unit kick which is given by the transfer matrix element, $T_{ij}(design + error = machine)$.

The inputs to COMFORT-PLUS provided by the user are:

1. Beam Trajectory Test data set, $T_{ij}(machine)$
2. COMFORT dataset (quadrupoles to be varied in the fitting)

The fitting process is:

COMFORT-PLUS uses NPSOL and COMFORT to find the quadrupole strength errors by minimizing the differences between the machine and the model in either or both planes. NPSOL starts with the design quadropole strengths, calculates $T_{ij}(model)$, and fits to the machine $T_{ij}(machine)$ by adjusting the quadrupole strengths. The "figure of merit" for the fit is given by,

$$min \sum (T_{ij}(machine) - T_{ij}(model))^2$$

where the sum is evaluated over all monitors i.

The output from COMFORT-PLUS is:

1. The figure of merit of the solution.

2. The values of the fitted variables.

We tested this automated procedure for cases with simulated quadrupole errors in all five families of the NDR, each having a different error. For all cases with an error of less than 5%, the correct solution was found with the figure of merit equal to zero. For cases with a maximum error larger than 5%, the program sometimes found the wrong solution which corresponded to an local minimum with a figure of merit greater than zero.

Recent Applications

A recent application of COMFORT-PLUS involved the commissioning of the return line from the NDR, NRTL. The procedure was as follows. A kick was introduced at a corrector magnet near the beginning of the NRTL. The value of the kick was varied and a discrepancy between the model prediction and the beam position monitor data was discovered at monitor 454 (see Fig. 1).

The strengths of several quadrupole magnets just upstream of monitor 454 were varied. When only one of the quadrupole magnets was varied, the best fit to the data occurred for a 2% error in the quadrupole magnet directly upstream of the monitor. Figure 2 shows actual beam data and the model prediction including the 2% error in the quadrupole.

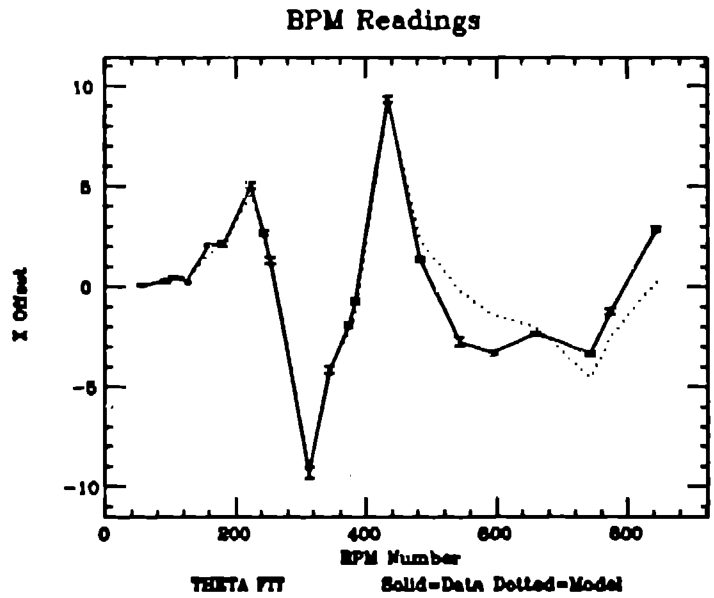

Fig. 1 - Beam trajectories for NRTL, actual beam data and design values (model).

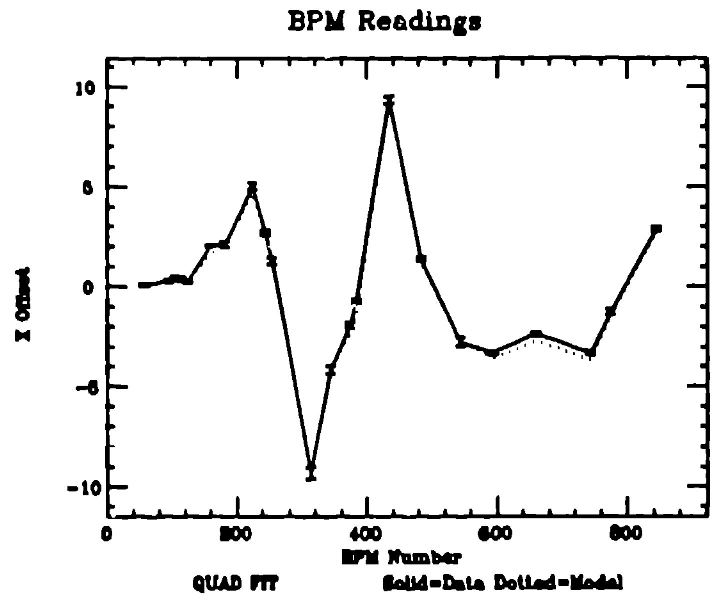

Fig. 2 - Beam trajectories for NRTL, actual beam data and fitted model prediction.

In another application, several NDR quadrupole magnet families were varied in strength in an attempt to obtain a good fit to the beam data. Table 1 shows the results of three experiments. In column A, five quadrupole families were allowed to vary. The percentages refer to the change from the starting value to the fitted value. The last three entries had fitted values too different from their starting values to be physical. In column B, the last three quadrupole families were fixed at zero and the first two families were allowed to vary. In this case the fitted values obtained were significant but still feasible correction factors. In column, C the first two families were fixed at their value found in column B and the last three families were again allowed to vary. The fitted values of QFI and QDI essentially cancel each other and QFM is negligible. The fitted values for QF and QD (-4.7% each) agree well with the -4% found by "knobbing" the model. These results show the neccessity of careful experiment design and interpretation.

Case	A	B	C
QF	-3.5%	-4.7%	-4.7%
QD	-4.0%	-4.7%	-4.7%
QFI	-11.0%	0.0%	2.0%
QDI	-5.7%	0.0%	-2.0%
QFM	10.0%	0.0%	1.0%

Table 1

Recently the SDR was recommisioned and during the commissioning runs it was found that no beam could be stored into the "design" configuration. Beam was finally stored by manually adjusting the strength of the QD and QF magnet families to change the machine tunes. The strength of these quadrupole magnets in $1/m^2$ for the "design" and "knobbed" configurations are shown in Table 2.

Magnet	Design	Knobbed	%difference
QF	-18.276	-18.670	-2.2%
QD	17.884	18.624	4.1%

Table 2

In order to store beam, large changes were made in the strengths of the QF and QD families. The reasons for these large changes are discussed below.

With a stored beam, careful measurements of the change in the closed orbits due to kicks from several correctors were taken. COMFORT-PLUS was used to analyze the measured data in order to understand why it was not possible to store beam into the "design" machine configuration. After studying the results of the several runs of this program (the C_{ij} option), the most likely solution was found to be an error of -2% in the strength of the QD and QF families. Figure 3 shows a fit between the measured Dy_i (vertical closed orbit difference) values and the corresponding predictions by the model.

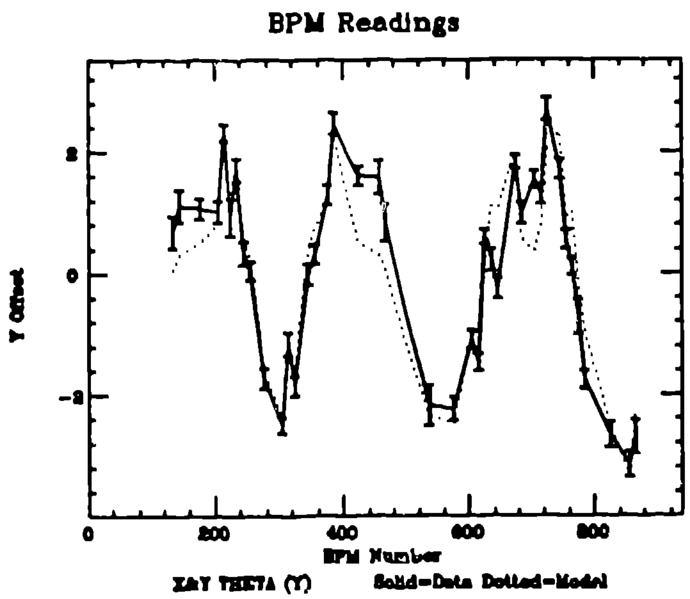

Fig. 3 - SDR vertical closed orbit data and design model prediction.

Figure 4 shows the actual data and model prediction with the best fit. The data and model are in very good agreement.

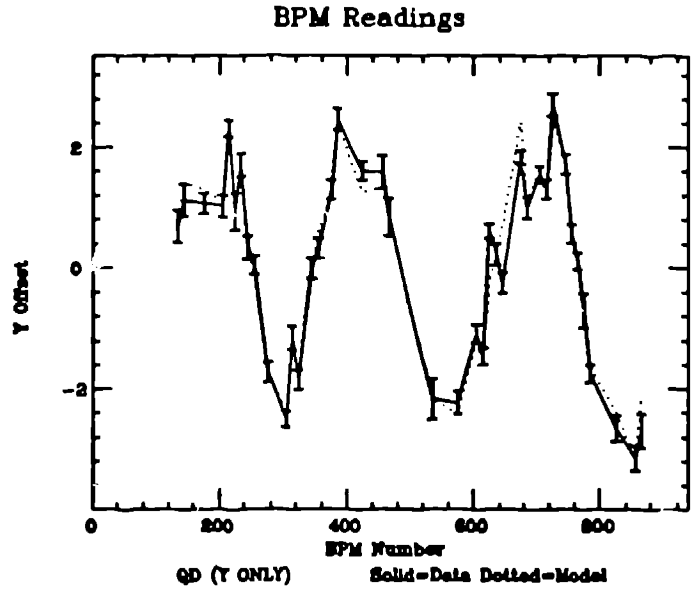

Fig. 4 - SDR actual data and best fit model prediction.

In order to check our solution, the tunes of the machine were measured. They were found to be within .006 of the values computed by the model using the correction factors. Table 3 gives the value of the measured tunes and the prediction from the model with and without the correction factor.

Tune	Design	Design-2%	Measured
ν_x	8.362	8.198	8.194
ν_y	3.45	3.264	3.272

Table 3

In order to understand why it was not possible to store beam into the "design" configuration, the machine tunes were calculated by reducing the design value of the strength of QD and QF by 2%. The vertical tune was found to be unstable which is consistent with experimental observation. Furthermore, using the corrected model, the beta functions were calculated for the "knobbed" configuration. The result shows a large mis-match in the beta functions corresponding to a beat factor of 50%.

Finally, the model was used to set up the machine using these correction factors to the "design" configuration with the desired tunes (ν_x=8.22, ν_y=3.12) and matched beta functions. With the machine in this configuration beam was stored immediately without any manual adjustment (the closed orbit corrections were left at the values of the "knobbed" configuration). The measured tunes were found to be within .003 of the model predictions. Some of the beam instabilities, which may have been caused by the large mis-match in the beta functions, disappeared. The capture efficiency was found to be nearly 100%.

Summary

COMFORT-PLUS has been used satisfactorily to find the beam focus errors in the NDR and SDR. The correction factors of the SDR were found to be about half as large as those for the NDR. Since both rings are almost identical in design, the reason for the large difference between the respective correction factors is not understood. However, the use of COMFORT-PLUS reduces the time it takes to find the errors manually by many orders of magnitudes.

This program will be used as an off-line program to analyze actual measured data for any SLC system. Since the input dataset for COMFORT-PLUS is similar to the input dataset of COMFORT, COMFORT-PLUS can be used on-line or off-line, on nearly any beam-line.

A limitation on the application of this procedure is that it depends on the magnitude of the machine errors. Another limitation of this program is that it is not fully automated since the user must decide, a priori, where to look for errors. Furthermore, since the figure of merit is never exactly zero because of noise in the measured data, the user also must evaluate the solution heuristically. Methods for automating the heuristic evaluations, *i.e.* "expert systems", have been discussed previously[7] and are being studied using a beam-line simulator.[8]

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