

MODELS and SIMULATIONS*

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On-line mathematical models have been used successfully for computer controlled operation of SPEAR and PEP. The same model control concept is being implemented for the operation of the LINAC and for the Damping Ring, which will be part of the Stanford Linear Collider (SLC).

Errors in construction and modification may cause an actual machine to be different from the ideal machine conceived in the design. When the machine parameter values calculated from the model are substantially different from the measured values, the model cannot be used for computer controlled machine operations such as changing operating configuration or correcting closed orbit errors or trajectory errors.

Simulations can be used to develop an empirical model based upon the measured values of beam parameters. The effects produced by suspected errors can be studied by simulating them with a model and comparing the results with measured values. In some cases, changes in the model can be found which minimize these differences. This is a possible method for finding an empirical model to represent an actual machine.

We have used this procedure to find an empirical model for the Damping Ring, which has been in operation for several months. Based upon the measured changes in closed orbits produced by known kicks from orbit correctors, an empirical model has been found which correctly predicts these measured orbit changes.

The purpose of this paper is to describe the general relationships between models, simulations and the control system for any machine at SLAC. The work we have done on the development of the empirical model for the Damping Ring will be presented as an example.

2. Modeling Programs and the Control System

For initial operation of a machine under computer control, it is very important that the on-line model of the machine be the same as the model used in the design calculations and error studies. Since the control model is the design model, the model works by definition albeit a system may not perform as predicted by the modeling. If such an event occurs, it would then be reasonable to investigate errors in other areas (design, fabrication, installation, or calibration), but not to be concerned with the accuracy of the modeling.

By the same reasoning, it would be desirable to incorporate the programs used in a machine's design into the control system in order to eliminate another possible source of error. A drawback to the use of the designer's programs for on-line machine control is that such programs are typically large, general purpose routines which require relatively large amounts of computer memory and are not as fast as one would like for an automated control system. Once a new system has been brought on-line and understood, faster and more compact programs should be developed and installed in place of the original design codes. To ease the process of code modification and replacement it is important that modeling programs be modular in nature. This is accomplished by requiring the specific modeling codes to accept input vectors and to return output vectors of information from or to appropriate driver programs. Modeling program replacement then becomes a minor localized perturbation on the control system.

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Communication through the database is a tool by which modularity of modeling programs can be insured. Use of the database also allows simultaneous development of interacting models by several different people. The database provides a well structured method by which modeling programs can communicate with those portions of the control program associated with the actual adjustment of power supplies while also isolating the task of modeling from the remainder of the control system.

In general, each of the modeling programs can be considered to be a stand alone computer code which computes the value of an output vector corresponding to the value of a desired input vector. Input vectors to the models include the users's specifications, usually entered from options selected using a touch panel, as well as other necessary data which is stored in the computer database. The information in the output vector is in turn saved in the database or in library files. For example, in a storage ring lattice model an input vector may contain such values as tunes, β and η at some specific locations, beam energy, etc.; the output vector may contain the values of the strengths of the ring elements. Database entries have been reserved for information relating to the state of elements in the machine. This includes the locations, lengths, current settings, and integrated field strengths of magnets, the beam energy gain associated with each klystron and the locations of beam position monitors. Information resulting from a modeling calculation that is not involved with the setting of power supplies (such as the calculated machine functions or the results of calculations which will appear on a graphics display) is not included in the database but is stored in local data files.

From a modeling point of view, it is considered poor practice to operate a machine by "tweaking" power supplies. It is possible to adjust the value of any or all of the beam parameters which are elements of an input vector by using a model. In addition, given that the power supply setpoints have been changed manually, models enable a user to calculate the corresponding machine parameter values. For example, it is possible to find the values of tunes, β and η for a storage ring lattice from the known values of the setpoints of the ring elements. Furthermore, an on-line model can be used to study the effects of changes on the beam parameter values without actually changing the setpoints of the elements. Such an "ignore hardware" feature allows a user to read the extant system settings, to calculate a change, and to predict the results of such a change before it is implemented. In this "ignore hardware" mode, models enable the user to evaluate the effects of any desired change in the machine and the subsequent effectiveness of schemes designed to compensate for those effects; this can be applied, for instance, to the study of error effects and possible error correction schemes.

It is possible to summarize the relationships between the modeling programs and the control system in a block diagram as shown in Fig. 1. The portion of the control system relevant to modeling calculations is enclosed in the inner circle. The possible interactions between the users, machine physicists, modelers and operators are indicated by the arrows on the outer circle. This structure was developed for the model calculations of PEP and will be used for SPEAR and SLC.

3. Simulations

In the design stage, simulations can be used to study the effects of changes in the machine element strengths on the beam parameter values, which includes the study of error effects and their correction.¹ Once the machine is operating, the beam parameter values can be measured and the imperfections of the machine can be studied by simulating their effects using models. Errors can be introduced into the model and their effects calculated. Machine imperfections may be located by inserting errors into the model which yield the measured effects. This method has been used to locate imperfections in the Damping Ring. The results of this study will be described in the following sections in order to illustrate an application of model simulation and to demonstrate some of the interactions between the users and the modelers as described in Fig. 1.

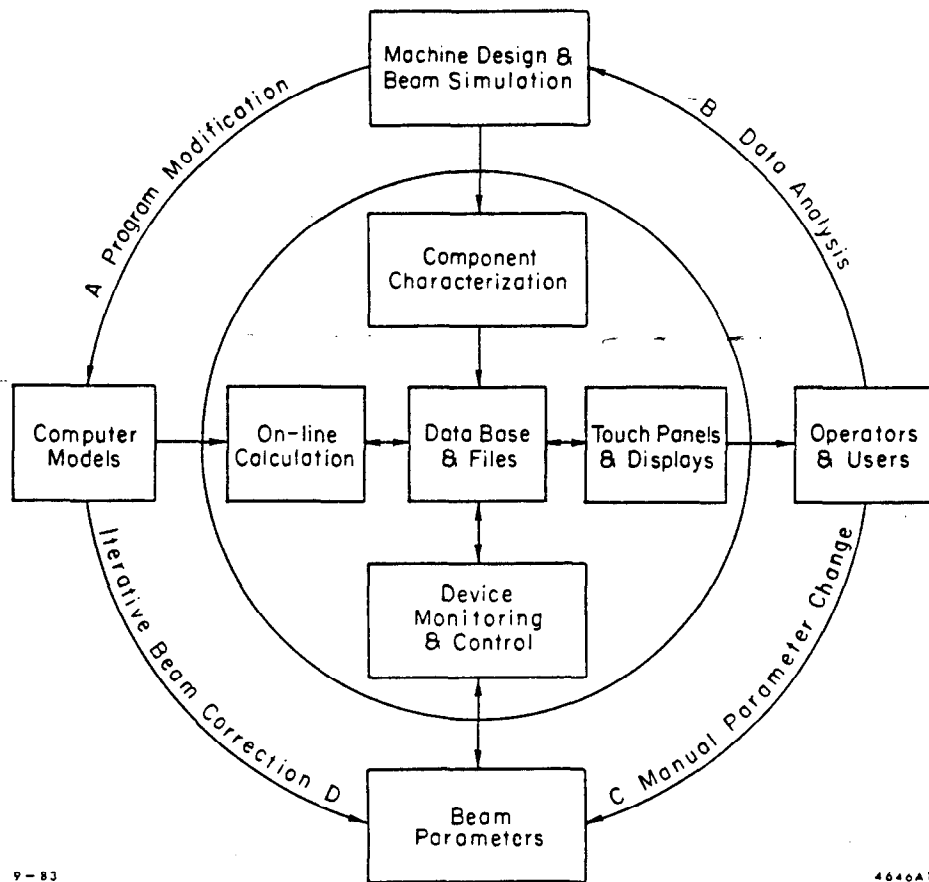


Fig. 1. A block diagram showing the relationships between model programs and the control system (inside the inner circle), and the possible interactions between users and modelers (on the outer circle).

3.1 LATTICE DESIGN

The ring lattice consists of two symmetric superperiods. Each superperiod has five repeated FODO cells, two half insertions and two matching sections. The beam is injected and also extracted in the half insertions at the ends of one of the two superperiods. The circumference of the ring is 35.268 m. It has 40 bending magnets and six families of quadrupole magnets, which define the first order optics of the lattice.

The Damping Ring lattice was designed using the magnetic lattice design code MAGIC.² This code solves for the strengths of the six families of quadrupole magnets in the machine in order to obtain a desired set of six beam parameter values which define the operating configuration of the ring. Two of the configuration parameters are the horizontal and vertical tunes. Two other configuration parameters are the values of the horizontal and vertical β function at the midpoint of the insertion region where the beam is injected into the ring. The fifth configuration parameter is the value of the energy dispersion function, η , at the same point. The sixth configuration parameter is α_x at the beginning of a FODO cell which is needed to impose the condition of periodicity on the horizontal β function in the periodic portions of the lattice.

Using MAGIC, the design of the lattice was studied and a suitable set of the tune, β and η values were chosen to be the design parameter values.³ The object for the control system is to set the magnets to achieve these design parameter values in the actual machine.

3.2 ON-LINE LATTICE MODEL

We have developed a general purpose lattice computation program, COMFORT,⁴ which is smaller and faster than MAGIC. COMFORT is intended to be the replacement of MAGIC for modeling and simulation of storage rings. In the control system, the Damping Ring model is a COMFORT dataset. The input vector to the model is the set of desired values of tune, β and η as described in the previous section. These values can be changed via touch panel commands as desired by the user. COMFORT calculates the the output vector, which contains the values of the magnet strengths, and sends it to the database. The control system converts these strength values to magnet current setpoint values and then adjusts the power supplies accordingly.

When the machine is operating under computer control, the values of the quadrupole strengths are converted into power supply setpoint values using magnetic measurement data which resides in the database. (See Fig. 1).

3.3 BEAM PARAMETER TEST

The Damping Ring has been operating for several months under computer control but not using the on-line model. When it was first turned on, the users tried to store beam using the design configuration but failed. As a last resort, they "tweaked" the power supplies manually via software knobs which can be assigned to each power supply with a touch panel command. They succeeded in storing beam in this experimentally obtained configuration. The beam parameters for this configuration have been measured and studied extensively. In addition, in order to study the variation of β functions in the lattice, changes in the closed orbit caused by known kicks at many of the orbit correctors have also been measured. It was found that the measured tune, β and η values were substantially different from the ideal values corresponding to the design configuration. Furthermore, when the strengths of the ring elements from the experimental configuration were used in the model, unstable tunes were predicted. It was impossible to change the machine tune, β and η values from the measured values to the desired design values or to correct the measured orbit errors conveniently without a working model.

3.4 MODEL MODIFICATIONS

In order to compensate the natural chromaticities of the ring, the pole faces of the bending magnets have been modified to produce sextupole fields. At one end, a "nose" piece was added, while at the other end a "hole" was cut from the pole face. It was discovered that the design lattice calculation had not been updated to include the effects of these modifications.

To correct this omission, the model was changed such that one thin-lens quadrupole, Q_n , was added to the end of the bending magnet with a nose and another thin-lens quadrupole, Q_h , was added to the other end. We assumed that the value of Q_n or Q_h would be the same for all of the bending magnets. Using COMFORT, we found the values of Q_n and Q_h needed to fit the measured horizontal and vertical tune values. The result was a configuration which was totally different from the design configuration, as can be seen in the differences between the machine functions of the design lattice and of this model lattice as shown in Figs. 2 and 3.

Using this model, we calculated the changes in closed orbit values at the beam position monitors for the corrector kicks which were actually used in perturbed orbit measurements. We found that the orbit changes produced by the horizontal corrector kicks agreed very well with the results of the model calculation, while the vertical orbit changes did not, as shown by two typical cases in Figs. 4 and 5. These results indicate that there are errors in the actual machine which effect the beam in the vertical plane and not in the horizontal plane.

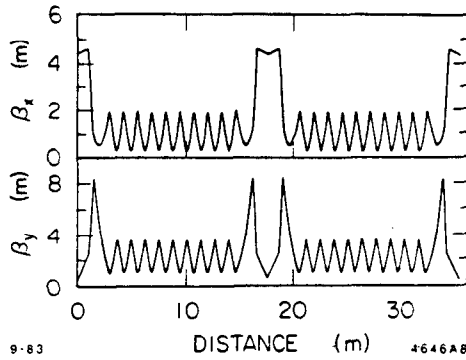


Fig. 2. A plot of the β functions along the Damping Ring for the design model.

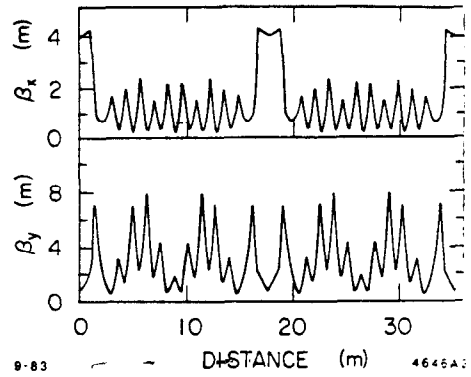


Fig. 3. A plot of the β functions along the Damping Ring after correcting the model to include the edge focusing effects from the bending magnets.

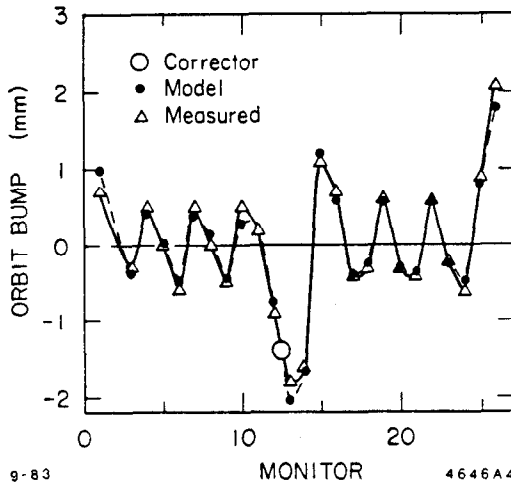


Fig. 4. A plot of the measured and predicted horizontal orbit changes caused by a given kick from a corrector near Monitor 12

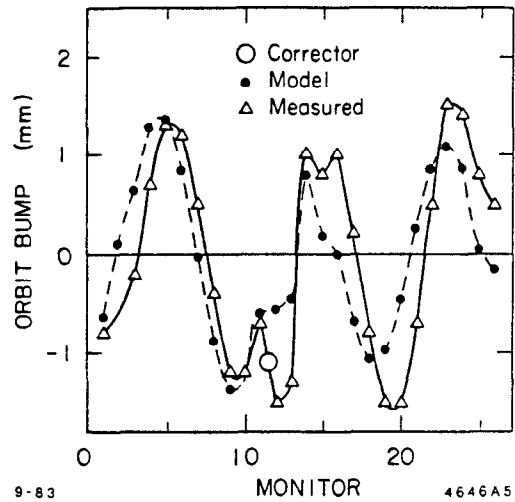


Fig. 5. A plot of the measured and predicted vertical orbit changes caused by a given kick from a corrector near Monitor 11.

3.5 ERROR SIMULATIONS

We assumed that the focusing error would be in one of the three families of horizontally defocusing quadrupoles where the vertical β function is large compared to the horizontal β function since the discrepancies were observed to be in the vertical plane.

A program, ORBFIT, was written to study the effects of this type of error on the closed orbit. The following tasks were performed by ORBFIT in this study:

1. For any given error to be studied the values of Q_n and Q_h are varied to fit the measured tune values using COMFORT.
2. COMFORT also computes the transfer matrix between a kick at any corrector and the change in orbit at any monitor for the lattice obtained in step 1.
3. Using this matrix, the value of corrector kick is adjusted to minimize the difference between the predicted orbit changes and the measured changes for a given corrector.
4. Step 3 is done for all of the correctors used in the measurements.

It was hoped that an error in one of the three families of defocusing quadrupoles could be found such that the changes in closed orbit predicted by the model would agree with the measured changes for known corrector kicks. The outputs from ORBFIT for cases with different errors in each of the three defocusing quadrupole magnet families can best be compared by considering the value of the rms ratio, which is defined as the rms of the difference between predicted and measured values divided by the rms of the measured values. The rms ratio would ideally be zero for a perfect fit between the prediction and the measurement.

The ORBFIT output for a reference case without any errors in the ring quadrupole magnet families is shown in Fig. 6. Since the rms values of the measured orbit changes are typically 0.5 mm, an rms ratio of 0.2 corresponds to about 0.1 mm, which is the order of magnitude of the errors in the measurements. It can be seen that the model predictions work well for the horizontal plane but not for the vertical plane.

Many different values of errors in each of the quadrupole families have been studied. Comparison of the results indicates that errors in the QDI magnet family give the smallest rms ratio values. QDI is the defocusing magnet nearest the insertion where the beam is injected or extracted. Since identical errors were introduced into each of the four QDIs, the resultant lattice has the same symmetry as the design lattice. The ORBFIT result for a -3% error in the QDI gradient is shown in Fig. 7.

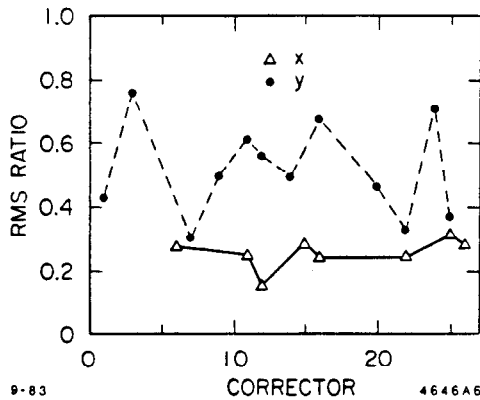


Fig. 6. A plot of the output from ORBFIT to be used as a reference case in the error simulation study.

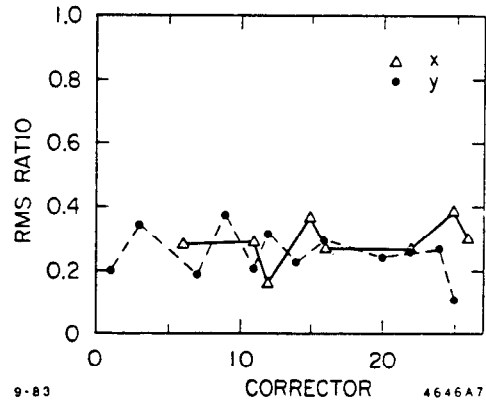


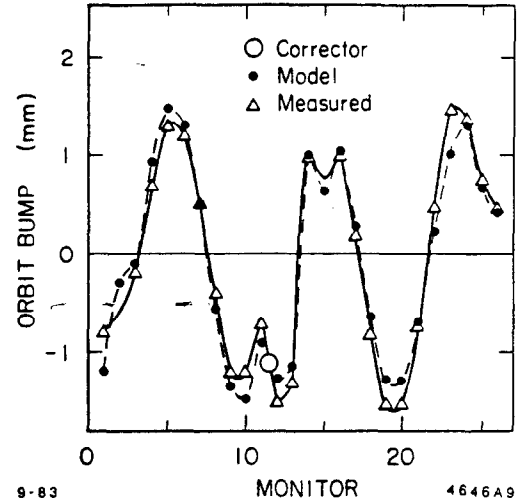
Fig. 7. A plot of the output from ORBFIT for the case with an error of -3% in the strength of the insertion defocusing quadrupole magnets.

By comparing Figs. 6 and 7, it can be seen that the rms ratios for the vertical plane have been improved substantially in the empirically fitted model. For example, the orbit changes due to kicks by the vertical corrector in position 16 have an rms ratio of 0.608 using the reference lattice; the rms ratio has been reduced to 0.195 by using the empirical lattice. The orbit changes predicted for a kick by this corrector using the empirical lattice is shown in Fig. 8, which can be compared with the plot in Fig. 5 to see the improvement.

3.6 EMPIRICAL MODEL

We have seen that it is possible to modify the model empirically by studying the measured closed orbit changes due to known corrector kicks. In the empirical model, the QDI family is assumed to have an error in the calibration used to convert the quadrupole strength to magnet current. An error of -3% has been found to be optimum. The values of Q_h and Q_n needed to model the edge effects in the bending magnets in this model are equivalent to pole face rotations of -5.5 and -11.5 degrees, with the minus sign indicating horizontal focusing effects. These values are somewhat dependent upon the angular and positional displacements of the beam away from

Fig. 8. A plot of the measured and predicted vertical orbit changes caused by a given kick from a corrector near Monitor 11. The predicted orbit change was calculated with the empirical model.



the design orbit at the entrance and exit of the bending magnets and hence could actually vary from magnet to magnet.

Changes in tune, β and η values can be predicted using this empirical model, as well as changes in the closed orbit produced by given corrector kicks. Orbit correction schemes based upon least square minimization of the closed orbit errors can also now be applied.

Thus far we have only included corrections in this empirical model which do not alter the symmetry and superperiodicity of the design lattice. Figure 9 shows a plot of the β functions for this empirical model. In order to improve the model further, it may be necessary to study the effects of errors which do not occur symmetrically.

Figure 10 shows a plot of the measured horizontal η function at the monitors. It can be seen that the η function does not have two-fold symmetric superperiods. An asymmetric model will be needed for our understanding of this anomalous η function. Development of a new code, ETAFIT, which minimizes the difference between measured η function values and values predicted by the model by introducing asymmetric errors into the model is in progress.

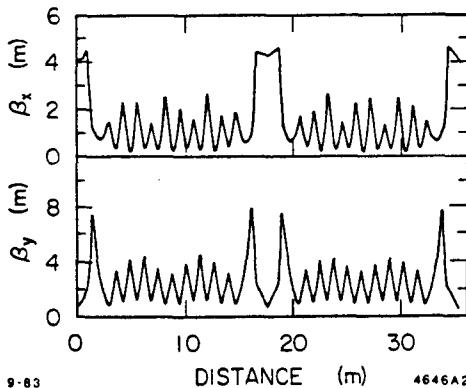


Fig. 9. A plot of the β functions along the Damping Ring for the empirical model.

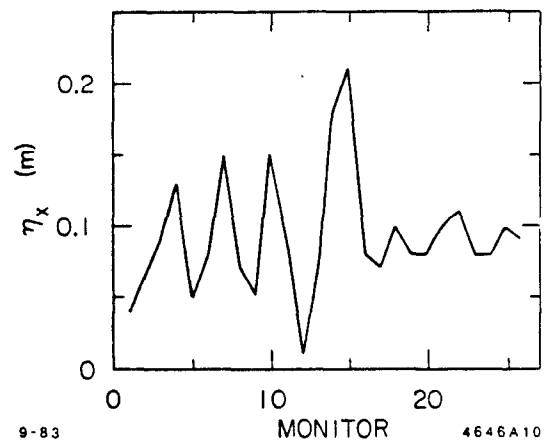


Fig. 10. A plot of the measured horizontal η function.

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