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EXPERIENCE WITH ALGORITHM-GUIDED TUNING OF APS-U UNDULATORS*

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Abstract

The Advanced Photon Source (APS) is undergoing a major upgrade to its storage ring. The APS Upgrade (APS-U) project plans to build over 40 new hybrid permanent magnet undulators (HPMUs) and rebuild over 20 existing HPMUs. To meet the APS-U undulator requirements, the quality of the undulator magnetic field needs to be fine-tuned to the specifications. The traditional methods that depend on the tuning specialist's experience are not desirable for tuning large quantities of undulators. We developed algorithms that automate the tuning of permanent magnet undulators. For tuning of the undulator trajectory and phase, the algorithms optimize the tuning parameters with differential evolution-based global optimization.

The algorithms have been successfully applied to 24 APS-U HPMUs. The results and experiences of the tuning are reported in detail.

INTRODUCTION

Undulators are the key instrument for producing synchrotron radiation. A permanent magnet (PM) is the most widely used source for generating the magnetic field in an undulator. Errors in the PM blocks, as well as the mechanical components, lead to errors in the fields of HPMU devices, which degrade the quality of radiation or disturb the operation of electron beams.

The RMS phase error indicates how seriously the radiation will be degraded. The APS-U requires that its HPMUs have an RMS phase error better than 3° for all operating gaps [1]. To meet this specification, the trajectory and the phase error have to be tuned.

In the past, undulator tuning in the APS was done largely based on the experience of the tuning specialist, which could be very time consuming. More efficient methods that minimize the tuning effort are needed for the APS-U HPMUs since 60 devices have to be tuned within a relatively short period of time.

A semi-analytical method for HPMU trajectory tuning that works well for trajectory tuning of one gap [2] was developed. A genetic algorithm was reported to be successfully used in the sorting and shimming of PM-based undulators [3].

In this paper, we describe the differential evolution-based algorithm for trajectory and phase tuning recently developed at the APS and the practical results of its implementation on APS-U HPMUs.

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TRAJECTORY TUNING

The $x(g;z)$ trajectories are first calculated from Hall probe measurement data taken at n_{gap} different gaps. The g is the index of the gap. We are interested in the trajectory walk-off, so the linear component in $x(z)$ has been removed using polynomial fitting. For trajectory tuning purposes, we define the initial period-averaged trajectory at the g-th gap as

$$X_0(g;i) \equiv \int_{z_i-\lambda_u/2}^{z_i+\lambda_u/2} x(g;z)/\lambda_u \, \mathrm{d}z, \tag{1}$$

where $i \le n_{poles}$ is the index of the poles, and z_i denotes the z-position of the center of the i-th pole. In this way, the sinusoidal oscillation component of the trajectory is neglected, and the trajectory at one gap is represented by an array with length equal to the total pole numbers. Data to be processed are reduced; hence, the computing efficiency could be improved. $X_0(g;i)$ is the starting point of the trajectory optimization.

Signature and Prediction Function

Two general types of shims are used at the APS for trajectory tuning, namely side shims and surface shims [4]. A shim creates a localized dipole field that kicks the electron beam. For simplicity, we assume the kick takes place within the range of one pole, i.e., only the integrated dipole component matters. According to our experience, this assumption does not introduce observable errors. We found that due to the saturation effect, the kick strength of some types of shims is not exactly proportional to the thickness of the shim, therefore, side shims of different thicknesses are regarded as different types and are indexed separately.

The effect on the trajectory of the shim with type index j that is installed on k-th pole could be described by a piecewise function

$$S(j,k,g;i) = \begin{cases} 0, & i \le k \\ \alpha_j(g)\cdot(i-k)\cdot(-1)^k, & i > k \end{cases} \tag{2}$$

where $\alpha_j(g)$ denotes the deflection angle at the g-th gap produced by the shim when it is installed on an even-number pole. Again, the linear component in $S(i)$ should be removed. This is done numerically, and the resultant function is denoted as $S'(j,k,g;i)$, which is called the trajectory signature of that shim. An example of trajectory signatures of a side shim is shown in Fig. 1.

Since only the integrated dipole field of the shim matters in our assumption, the trajectory signature could be measured either by Hall probe measurement or long coil measurement. In practice, we found the signature of shims from the Hall

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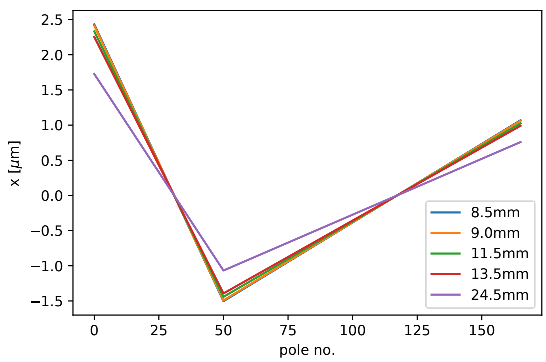

Figure 1: The gap-dependence trajectory signatures of one pair of 1-mm-thick side shims that were placed on pole # 50 of a 27-mm-period device.

probe measurement agrees well with that from the long coil measurement.

With the trajectory signatures prepared, we can construct a function that predicts the trajectory at a gap g if a shim of the j-th type is installed on the k-th pole,

$$X_p(j,k,g;i) = X_0(g;i) + S'(j,k,g;i). \quad (3)$$

If multiple shims are installed, we have the prediction function for trajectory tuning

$$X_p(\{j,k\}_m, g; i) = X_0(g;i) + \sum_{t=1}^{m} S'(j_t, k_t, g; i), \quad (4)$$

where m is the total number of shims that are installed on the poles. The t-th shim is of type j_t and is installed on the k_t pole.

Optimization Solver

We create an error function based on Eq. (4) to describe the straightness of the trajectories at all gaps after m shims are installed:

$$F_{err}(\{j,k\}_m) \equiv \sum_{g=1}^{n_{gaps}} w(g) \cdot rms(X_p(\{j,k\}_m, g; i), \quad (5)$$

where $w(g)$ denotes the weight of each gap. The objective of the trajectory tuning calculation is to find the the m sets of $\{j,k\}$ that satisfy

$$F_{err}(\{j,k\}_m) \to min. \quad (6)$$

Since j and k take discrete values, Eq. (6) cannot be solved by the least squares method. For each shim, there are ~ 150 choices for the shim location and ~ 5 choices for the type of shim. It is impossible to enumerate all the possible choices of parameters when $m > 4$.

Global optimization algorithms can be used to solve Eq. (6). We found that widely used general-purpose optimization algorithms, such as genetic algorithms and simulated annealing-based algorithms, work well in this scenario. A variant of the genetic algorithm called differential evolution [5] was chosen as the solver for its high computing efficiency.

For each specific HPMU trajectory tuning, the user needs to tell the solver the weights $w(g)$ and the total number of shims m. Usually, heavier weights should be given to smaller gaps. Due to the simplicity of the mathematical formulation, one round optimization process could be done in several minutes by an ordinary desktop PC when $m = 8$.

A practical example of trajectory tuning guided by the optimization solver is presented in Fig. 2. F_{err} in this example was significantly reduced by only one round of trajectory tuning.

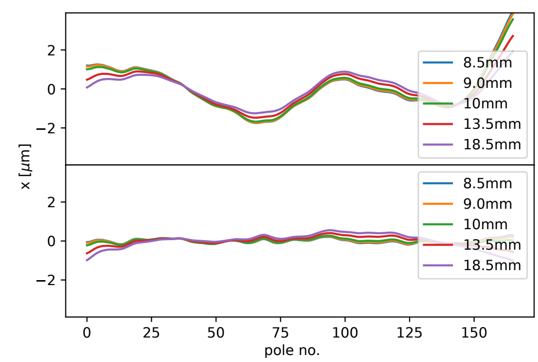

Figure 2: Period-averaged trajectories of a 27-mm-period device before (top) and after (bottom) being corrected by side shims. These were achieved in one round of tuning by installing side shims on six poles. The electron energy is 6 GeV.

The side shims and surface shims have kick strengths that vary differently across gaps. This feature is helpful to ensure the trajectories at different gaps are straight. However, the use of surface shims is avoided because they not only change the trajectory but also create unwanted phase error change as well as significant normal sextupole components. Among the 24 APS-U HPMU devices that have been tuned, only two have surface shims used for trajectory tuning.

PHASE ERROR TUNING

Trajectory tuning improves the phase error. Phase error corrections are still needed to meet the specification that the RMS value must be less than 3° for the APS-U HPMUs. The first means of phase correction is the newly developed "phase-based gap shimming" method, which is presented in a separate paper in these proceedings [6].

When the RMS phase error specification is still not met, another method of phase error tuning is to use a surface phase shim that covers the magnet and touches two neighboring poles. Such a shim reduces the field at the two poles by equal magnitudes; therefore, the phase advance between the two poles is reduced, but the angle of the electron remains unaffected.

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The surface shim-based phase tuning shares the same method as the trajectory tuning after two modifications in the prediction were made.

- Trajectory in the prediction function is replaced by the radiation phase error at each pole.
- Phase error signatures are fed to the prediction function.

The parabolic components in the initial phase error and the phase error signatures are removed because that phase error in an HPMU could be compensated by setting the gap taper. Similarly, we assume the phase change caused by a phase shim takes place between two neighboring poles. Unlike the case of trajectory, the phase correction by surface shims can only change the phase error by a negative amount. The phase error signatures of a surface phase shim are shown in Fig. 3.

Figure 4 demonstrates the effect of a round of phase tuning based on the solution from the optimization solver. The RMS phase error at a 8.5-mm gap (which is the minimum operation gap) was reduced from 5.2° to 2.5° by surface phase shims installed at five locations, and the installation took only 6 minutes. The phase changes from this round of tuning are shown in Fig. 5.

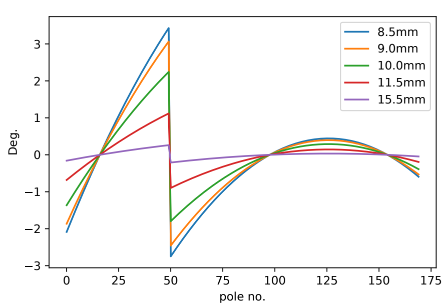

Figure 3: The gap-dependence phase signatures of one pair of 0.1-mm-thick phase shims that were placed between poles # 50 and # 51 of a 23-mm-period HPMU device.

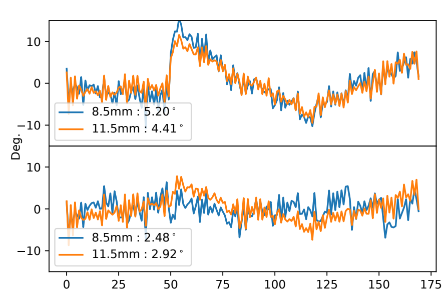

Figure 4: Phase error of a 23-mm-period undulator before (top) and after (bottom) being corrected by surface shims. A higher priority was given to the 8.5-mm gap in this case.

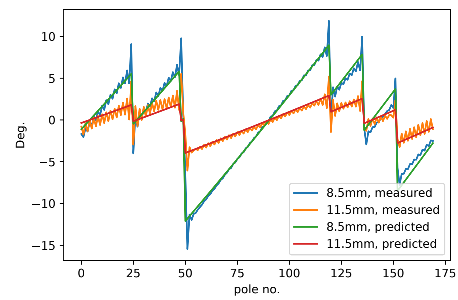

Figure 5: Comparison of predicted phase change and real phase change caused by phase shims at five locations.

From Fig. 5 we can see that the phase changes by the installed surface shims agree with the prediction, although there are small-amplitude oscillations of phase error around the locations where the shims were put.

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