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A FAST AND ACCURATE METHOD TO SHIM UNDULATOR USING MULTI-OBJECTIVE GA*

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Abstract

GA (Genetic Algorithm) is one of the most excellent methods to search the optimal solution for a problem, which has been applied to solve various problems. It is hard to estimate shim applied on raw undulator precisely. There are many methods have been developed to solve the problem. In this proceeding, we proposed a fast and accurate method to conclude the shim using multi-objective GA. A multi-objective objective function was set, and multi-objective optimization was also implemented. The evolution time is reduced by setting optimal evolution parameters. To demonstrate the method, we also finished some test on a prototype undulator U38. As a result, it can be achieved only by shimming three times that all the parameters of trajectory center deviation, peak-to-peak error and phase error satisfied the requirements.

INTRODUCTION

Light sources based on accelerator, including Synchrotron Radiation (SR) and Free Electron Laser (FEL), use extensively undulators creating a periodic magnetic field for the production of intense of radiation for users [1, 2]. The common-used permanent magnet undulator was invented by K. Halbach in 1980's and contains two magnet and pole arrays [3]. Imperfections and errors are inevitable during design and manufacture of undulators, such as positioning errors of the magnets and poles, small differences of magnetization value and direction from one magnet block to the next, the inhomogeneities of the magnetization inside a volume of a single block. These will introduce magnetic field errors [4,5]. Uncontrolled magnetic field errors of undulators, including electron trajectory center deviation, peak-to-peak error and phase error, will degrade light sources [6]. There are various shimming methods for correcting them in order to optimize undulator performance. The shimming methods are based on the fact that either moving a magnet or a pole (mechanical shim) or by placing some thin piece of iron at the surface of the magnet (magnetic shim) can make a small local correction of the magnetic field [7]. To shim undulator, it must be concluded that how much to move or how thin piece to place first. Many methods have been developed to solve the problem. In this proceeding, a method based on multi-objective GA to conclude shim fast and accurately was proposed, and in order to demonstrate the method prototype undulator U38 was also shimmed.

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METHOD

Multi-Objective GA

GA was first put forward by professor J. Holland in 1975 and had a prosperous development era in the 90's. Now, GA has been applied in various areas and especially shows many advantages in combination optimization problem.

In an optimization problem based on GA, there is a population consisting of candidate solutions of the problem (individuals). Every candidate solution in population has a set of properties (chromosomes) which can mutate and crossover. An initial population usually contains individuals generated randomly or as required, which is evolved toward better populations. The evolution is an iterative process, and the population in every iteration is a generation. In every generation, the fitness of every individual is evaluated. Portion of individuals is selected from the current population, where fitter individuals decided by fitness are more likely to be selected. Then, chromosome of every individual being selected is modified (crossover and mutation) to form a new generation. The new generation of candidate solutions is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population.

In practical optimization problem, there are usually many objectives, and in most cases the objectives are conflicting each other. The weight coefficient transformation method gives the jth sub-objective function $t(p_1,...\ (p_l)$ weight coefficient w_j, and all k sub-objective functions are weighted linearly to form a new objective function T (Eq.1). By this method, the multi-objective optimization problem is transformed into a single-objective optimization problem.

$$T = \sum_{j=1}^{k} w_j t_j(p_1, \ldots, p_l) \quad (1)$$

Model Setup

Model setup includes the following steps:

- *S(z)*, the relation between correction of local magnetic field distribution and minimal shim is built either by calculation or by measurement.
- For undulator with $2N_u$ modules, the correction of local magnetic field distribution for other shim can be concluded by multiplying a coefficient C_n (n is module's number) with *S(z)*. Now, the problem was changed to find optimal C_n for every module.

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- The new magnetic field distribution $B_{m+1}(z)$ was generated by adding C_n*$S(z)$ of every module to old magnetic field distribution $B_m(z)$ like Eq. 2.

$$B_{m+1}(z) = B_m(z) + \sum_{n=1}^{2N_u} C_n S(z') \quad (2)$$

- Integer C_n was converted to binary for genetic representation, and all C_ns formed a binary array.

APPLICATION

Prototype Undulator U38

Prototype U38 is a hybrid planar undulator with two antisymmetric Halbach-type magnetic arrays. Each array includes 11 periods made of NdFeB blocks and DT4 blocks. The gap of U38 is fixed at 18 mm. One magnetic module is shown in Fig. 1, where one DT4 block and two half-NdFeB blocks form a sandwich-like structure. So, one period contains two modules. Mechanical shim was implemented by inserting copper pieces with various thicknesses between magnetic modules and beam to modify local field. Besides, to simplify work only magnetic modules of upper magnetic array were adjusted. Correction of local magnetic field after one module displacing of 0.001 mm can be seen in Fig. 2.

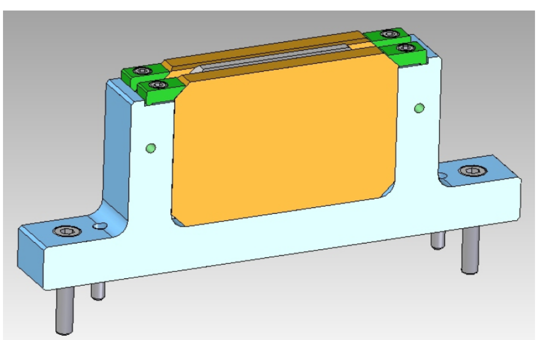

Figure 1: One sandwich-like magnetic module.

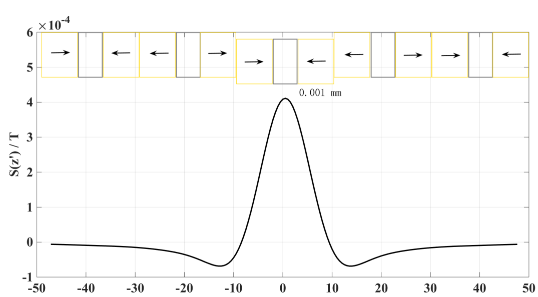

Figure 2: Correction of local magnetic field after displacing of 0.001 mm for one magnetic module.

For U38, there are three specifications must be reached, including trajectory center deviation < 0.2 mm, peak-to-peak error < 0.5%, and phase error < 5 °.

Objective Function

As mentioned above, prototype U38 has three specifications must be reached, so it's a multi-objective problem. Objective function was defined as follows:

- Providing the electron energy of 8 MeV, trajectory $x(z)$ was calculated by numerically integrating magnetic field distribution twice like Eq. 3, and then trajectory center deviation Δx_{rms} was concluded.

$$x(z) = -\frac{e}{\gamma m_0 c}\int_{z_{start}}^{z_{stop}} \left(\int_{z_{start}}^{z''_{stop}} B(z)\mathrm{d}z\right)\mathrm{d}z'' \quad (3)$$

- The peak-to-peak error $(\Delta B/B)_{rms}$ was obtained by root mean square value of peak field dividing mean value of peak field.

- The distribution of phase was calculated using Eq. 4, where $\phi(z)$, λ_u, $\overline{K}$, c, m_0 and e represented phase, period length, mean value of undulator parameter, light velocity, electron mass in rest frame and electron charge, respectively [8]. Then, phase error $(\Delta\Phi)_{rms}$ equaled phase at poles minus $2n\pi$, where n was pole number.

$$\Phi(z)=\frac{2\pi}{\lambda_u(1+0.5\overline{K}^2)}\cdot \left(z+\left(\frac{e}{m_0 c}\right)^2\left(\int_{z_{start}}^{z_{stop}}\left(\int_{z_{start}}^{z''_{stop}} B(z)\mathrm{d}z\right)^2 \mathrm{d}z''\right)\right) \quad (4)$$

- The linear combination of trajectory center deviation, peak-to-peak error and phase error was defined as the objective function.

$$T(B(z)) = 10\Delta x_{\mathrm{rms}}+(\Delta\Phi)_{\mathrm{rms}}+500(\Delta B/B)_{\mathrm{rms}} \quad (5)$$

GA Configure

- The chromosome structure is shown in Fig. 3, which is a 6*$2N_u$-dimension array.

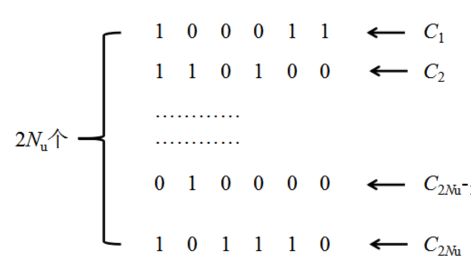

Figure 3: Structure of individual's chromosome.

- Commonly, the initial population is generated randomly, allowing the entire range of possible solutions. But, we filled initial population with zero to limit the number of modules must be moved.

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Table 1: Parameters of GA

Parameter	Value
Population size	200
Mutation rate	0.02
Crossover rate	0.8
Elitism	1

- It is commonly accepted that a certain amount of elitism speeds up optimization. So, it was decided to keep the best chromosome to next generation.
- The evolution will terminate when objective function satisfies the requirements.
- GA is a wide diverse group of algorithms, which qualitative working principles vary and our parameters of GA can be seen in Table 1.

Shimming Results

The shimming of prototype U38 was implemented as follows:

a. Measuring the magnetic field distribution

b. Calculating the optimal C_n for every module using GA

c. Shimming U38

d. Repeating process of a, b and c until the requirements are satisfied.

We finished three times shimming. The evolution of trajectory, peak-to-peak error and phase error with the shim number are shown in Fig. 4, Fig. 5 and Fig. 6, respectively. It can be seen the performance was improved during evolution. After three times shimming, the requirements were satisfied. The trajectory center deviation, peak-to-peak error and phase error are reduced to 0.15 mm, 0.49% and 1 °.

CONCLUSION

In this proceeding, We proposed a fast and accurately method to conclude the shim using multi-objective GA. The method was also applied to shim a prototype U38 to demonstrate. After three times shimming, the performance of U38 satisfied the requirements. The trajectory center deviation, peak-to-peak error and phase error are reduced to 0.15 mm, 0.49% and 1 °.

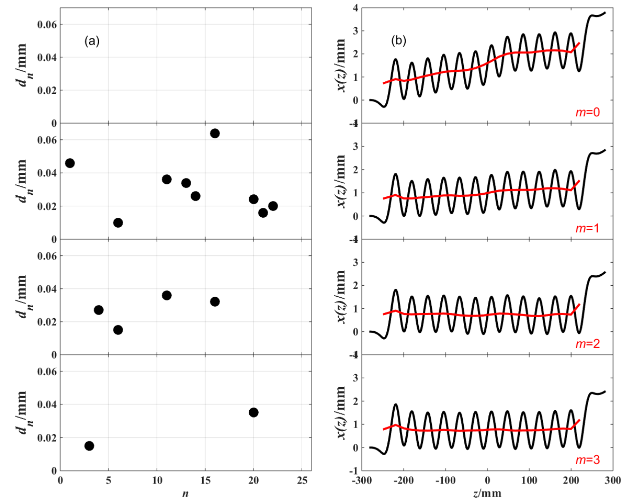

Figure 4: Displacement of one module (a) and evolution of electron trajectory and trajectory center (b).

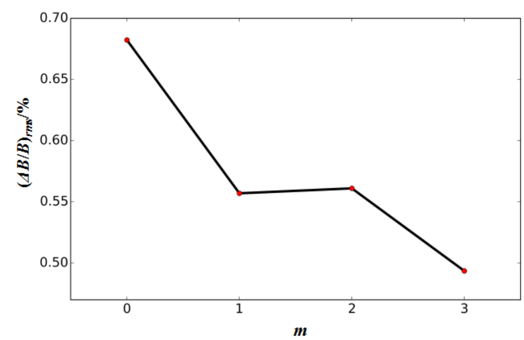

Figure 5: The evolution of peak-to-peak error.

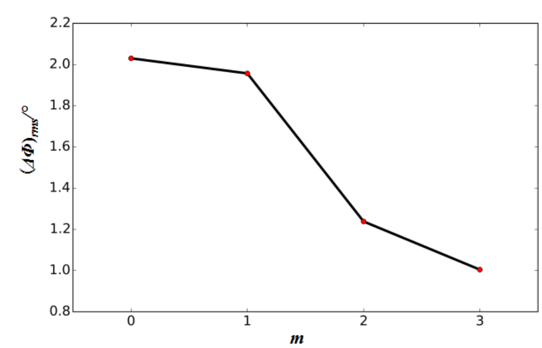

Figure 6: The evolution of phase error.

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