APPLYING MOGA TO SEARCH LINEAR LATTICE IN SOLEIL UPGRADE PROJECT

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Abstract

In the community of synchrotron radiation facilities, multi-bend structure becomes the trend of the storage ring design toward lower emittance. For SOLEIL upgrade project, the 7BA-6BA hybrid structure is one of the current options. This paper puts the focus on the 7BA section. There are many degrees of freedom to tweak and many constraints to follow. Here, the idea is to search and build the linear lattice utilizing Multi-Objective Genetic Algorithm (MOGA), which is efficient dealing with higher dimension optimization problems. Within MOGA, subsidiary matchings are performed to ensure certain criteria when the new generation is bred. Delicate designs and manipulations of the objective functions are needed, in order to have a better convergence without being trapped in a local minimum. The results will be shown and discussed.

INTRODUCTION

Pioneered by MAXIV's upgrade project [1], many third generation synchrotron light sources propose upgrade projects toward a diffraction-limited storage ring. Definitely more bending magnets are needed. In general the preferred structure is the multi-bend achromat (MBA) lattice.

SOLEIL light source is a state-of-the-art third generation synchrotron light source. The natural emittance is 3.9 nm-rad at 2.75 GeV, which is as low as 2.2 times the theoretical minimal emittance. The lattice features a double bend structure with 3 types of straight section lengths. It's a very compact ring in which straight sections occupy 46% of its total circumference (~ 354 m). At first the upgrade project aims at the emittance < 300 pm-rad. To replace the magnet sections with a MBA structure in such a compact ring, one of the biggest challenges comes from the limitation of space.

To design such a complicated linear lattice, it's better to dissect the problem into smaller pieces and build the lattice piecewise. How to appropriately dissect the problem may be an artisan work. As an example, a systematic strategy is proposed to search and construct a lower emittance lattice in the current SOLEIL's geometric configuration [2]. For problems with a small degree of freedom, a global scan is complete and feasible. However, for dimensions higher than 5, modern fast converging searching algorithms such as Genetic Algorithm (GA) or the particle swarm method are necessary.

When facing multiple objectives which in general can not be optimized simultaneously, some trade-offs have to be made. The purpose of multi-objective optimization algorithms is to find a set of optimal solutions in the objective space so that any good decision lays on it. This optimal set is called the pareto front.

GA has been proven efficient in dealing with high dimensional optimization problems. MOGA is the multi-objective version of GA. It has been introduced with success in the accelerator lattice design community [3–5]. For example, a MOGA package based on Elegant code for the sextupole scheme is developed at APS [3]. It finds the pareto front of dynamic aperture area and Touschek lifetime. The improvement of the lifetime has been experimentally verified at SOLEIL [6].

Lattice with small horizontal emittance and long free straight sections cannot be fulfilled simultaneously. Therefore the idea to use MOGA to help the design of the linear lattice is conceived. The goal of this research is to find the pareto front of the horizontal emittance v.s. the length of magnet sections. An in-house MOGA program is developed to handle the job.

MOGA SETUP

Lattice Structure

The chosen lattice to study is the hybrid 7BA structure. It is similar to the lattice which is firstly proposed by the ESRF upgrade project [7] and then adopted by many other projects [8, 9]. Nevertheless, there are some minor differences between the chosen lattice and the ESRF's hybrid 7BA structure. Instead of longitudinal gradients dipoles, we use combined function bending magnets. In addition, inspired by the anti-bends design [10], two small anti-bend are added in the focusing quadrupoles to further reduce the emittance. The schematics and the naming convention of half of this structure are shown in Figure 1. The total bending angle is 11.25° and the half straight section length is assumed to be 5 m.

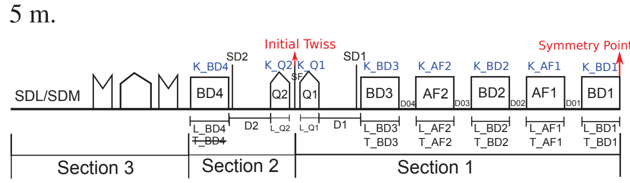

Figure 1: Magnet schematics of the hybrid 7BA lattice.

Lattice Construction Strategy

This lattice features the proper phase advances between two dispersion humps peaked between Q1 and Q2 for an effective sextupole scheme. The dispersion humps are formed by creating larger D1 and D2. These spaces are for defocusing sextupoles, while focusing sextupoles are located in the hump peak. Although the sextupole pairs are interleaved,

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this feature still gives the pseudo-cancellation of the non-linear sextupole effects. The third-order resonance driving terms are naturally small and good dynamic aperture can be expected.

To construct the optics piecewise, we use three matching steps on the three sections as shown in Figure 1. Section 1 and 2 form the bending section. The emittance depending on all bending magnets is determined in the bending section.

The three matching steps are as follows.

1. First, initial twiss parameters at the dispersion hump are chosen and propagated through Section 1. The slopes must be matched zero at the symmetric point. In addition, another strong phase relation $(\Delta\phi_x, \Delta\phi_z) = (\text{odd } \pi, \text{integer } \pi)/2$ is imposed.

2. Secondly, the same initial twiss parameters are reversely propagated through Section 2. This section plays the role of dispersion suppressor. The dispersion and its derivative must be suppressed for the achromat condition.

3. Finally, the zero slopes and the desired beta functions at the center of straight sections can be dealt with by the quadrupole triplet or doublet in Section 3.

The third matching is tricky. It can be carried out by another external matching program. Not all from the previous two steps can be matched to a stable solution. These bad solutions must be removed. The resulting quadrupole triplet length varies. Assuming they are roughly the same, the bending section length is equivalent to the magnet section length.

We're going to integrate the first two subsidiary matchings in our MOGA optimization. When a new individual is bred, the two matchings are performed. They are implemented by a numerical optimization code called NLopt [11]. Different methods have been tested and it was found that Augmented Lagrangian algorithm with Nelder-Mead simplex is efficient as the subsidiary algorithm.

Variables

There are many variables for this structure. All the lengths, gradients, and bending angles affect the linear optics. Careful choices of the boundaries are important. Besides, since we use the optics propagation method to construct the lattice, the initial optics at the dispersion hump can also be variables. However, due to the constraints of a good lattice, the degree of freedom is actually less. According to their different properties, the variables are classified into four categories.

1. *Initial twiss function at the dispersion hump*. There are six of them.

2. *Form factor of Section 1*. It includes all the lengths of the magnets and drift spaces in Section 1, plus all the bending angles. There are totally 16 of them. The space between the two quadrupoles in the dispersion hump is assumed 0.4 m. We use the variables in the first two categories as the MOGA variables.

3. *All the gradient components of Section 1*. We use these variables for the first matching, which gives zero slopes and proper phase advances at the symmetry point. There are 5 quantities to be matched and 6 variables are fairly enough.

4. *Variables of Section 2*. The bending angle of the outer bending magnet is not an independent variable. It has the responsibility to make up the total bending angle a constant. So there are 5 variables in this category.

Design Considerations

A satisfactory solution has the following properties.

1. Small horizontal emittance
2. Shorter bending section
3. Conserved total bending angle
4. Dispersion humps
5. Proper phase advances between humps
6. Zero slopes at the symmetry point
7. Achromat condition
8. Constraint on magnetic field
9. Constraint on maximal beta-function
10. Big beta-function decoupling around the humps
11. Small natural chromaticity

The first two items are the MOGA objectives. Items 3–8 are strong constraints which can be integrated and resolved by the subsidiary matchings. Item 3 is fixed by removing the dependency of the outer bending angle. Item 4 is done by the proper choice of the range of the initial twiss parameters. With penalty functions being designed properly, item 5 and 6 are resolved by the first matching, while second matching takes care of item 7. Item 8 can be dealt with by modifying the MOGA objectives. How to integrate items 5-8 will be addressed later.

At this moment, Item 9, 10 and 11 are not considered yet. For further improvement, Item 9 can be resolved by refining the matching program. Item 10 can be added by adjusting the objective. And Item 11 can be the third MOGA objective to be optimized. Moreover, we can combine Item 4, 10 and 11 to calculate the sextupole strengths, as the third MOGA objective.

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Objectives Design

The MOGA objectives have to be delicately tailored to handle the criteria 5, 6, 7 and 8. A smart manipulation on the MOGA objectives improves the convergence. Various objectives have been tried. Here we're going to present an example of an artisan design that works well. The trick is to use multiple levels of the objectives.

The first level deals with the criterion 8. The objective is a scalar function defined as a measurement of the excess dipole field. Its range lies between $(2, 3)$. As the generation evolves, the algorithm pushes the population toward criterion 8. If criterion 8 is satisfied, the objective moves to the next level.

The second level takes care of the goodness of matchings after a new individual is bred. This objective is a scalar function that measures the goodness of the two matchings. It is defined as the sum of the two matching penalties mapped to the range $(1, 2)$. The penalty functions of the matchings are designed so that the smaller matching penalty yields a better matching result. We define the matching with the penalty $< 10^{-6}$ as a good matching. As the generation evolves, the individual with better matching survives. If both matchings are good, the criteria 5, 6 and 7 are fulfilled, and the scalar objective enters the final level.

In the first two levels the objective is a scalar function. In practice, the two objectives are set identical to each other. The MOGA runs just like a single objective GA. These two levels provide the selection mechanism which filters out the infeasible solutions. Criteria 5, 6, 7 and 8 are guaranteed for individuals whose objectives reach the final level.

The actual MOGA is carried out in the final stage. In this level the scalar objective splits into two. They are also scaled to $(0, 1)$. They represent the actual quantities we care about: the emittance and the length of the bending sections. As the generation evolves, the algorithm picks and keeps the dominated solutions.

In many situations the objectives involve treating unbounded quantities. For example, the emittance can vary in a wide range. These quantities need a special treatment. An useful technique is to rescale the unbounded quantity to be bounded by a s-function. As an example of s-function, a standard logistic function defined as $f(x) = 1/(1 + e^{-x})$ maps x from $(-\infty, \infty)$ to $(0, 1)$.

SIMULATION RESULTS

Based on the framework defined by GAlib [12], a in-house MOGA program is developed to handle the job. The sorting algorithm is SPEA2 [13]. The data are stored in memory in SQLite3 format to improve the efficiency by saving DISK I/O time. As a reference, it takes about 28 hours for a single modern CPU to finish an iteration of 500 generations with the population of 300. The simulation result is shown in Figure 2. The objectives converge to level 3 quickly in a few ten generations. The pareto front and its improvement can be clearly observed. We pick four cases in the pareto front and compare their results in Figure 3.

In the pareto front the horizontal phase advances between the humps ($\Delta\phi_x$) found by the algorithm are always 3π. However the vertical phase advances ($\Delta\phi_z$) can be π, 2π, and even 3π. As the generation evolves, the algorithm pushes the pareto front to lower emittance. The solutions with higher $\Delta\phi_z$ gradually replace the cases with lower $\Delta\phi_z$ in the pareto front. Their nonlinear optimization is undergoing. In reality the phase difference doesn't have to be strictly (odd π, integer π). How much the criterion 5 can be relaxed needs further investigations.

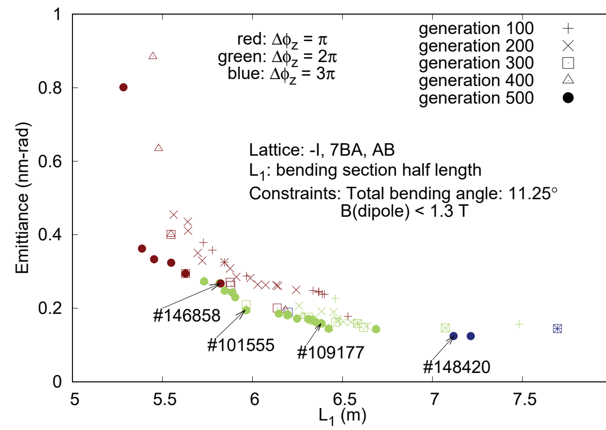

Figure 2: The objectives of every 100 generations: Horizontal emittance versus half length of the bending section.

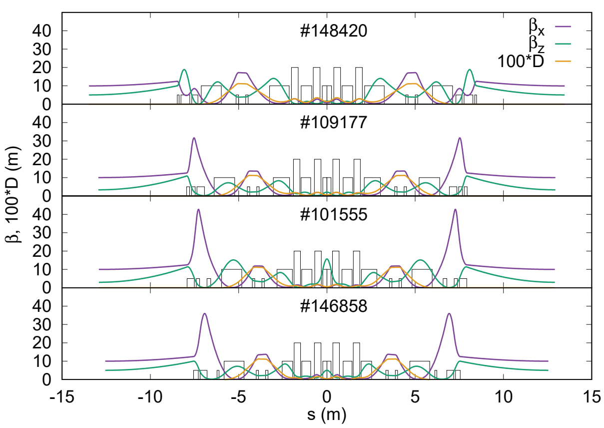

Figure 3: Optical functions obtained from MOGA for several cases of the pareto front.

CONCLUSION

This study demonstrates an approach to use MOGA to search linear lattices of the specific hybrid 7BA structure. To fulfill the design criteria, proper subsidiary matchings and the careful design of the objectives are necessary. The chosen objectives are the horizontal emittance and the bending section length. A pareto front is found for the decision making. Thorough explorations must include the matching in the straight section and the nonlinear properties. If being handled well, other lattice structures can be studied in a similar way.

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