ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-MOPH14

OPTIMIZATION OF CLOSED ORBIT CORRECTION USING ANT COLONY ALGORITHM IN HALS

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Abstract

In this paper, we present a method using correctors as few as possible while controlling the residual closed orbit within an acceptable level based on ant colony optimization algorithm instead of the ideal optical properties. We prove that this method works well with HALS.

INTRODUCTION

The Hefei Advanced Light Source (HALS) project [1], as a soft X-ray diffraction limited storage ring (DLSR), was proposed by National Synchrotron Radiation Laboratory with a beam energy around 2.4 GeV and the detailed lattice design is in progress.

To reduce the emittance of a DLSR, multi-bend achromat (MBA) lattices have been adopted. The main method to reduce emittance is to employ many strong quadrupoles which depress dispersion function and introduce chromatic aberrations that must be corrected with strong sextupoles [2]. In our first version lattice, the ring consists of 32 identical 6BAs with a nature emittance of 26.5 pm · rad [3]. The strong quadrupoles and sextupoles make the lattice sensitive to closed orbit distortion. Therefore, the closed orbit correction plays an important role in HALS's design.

Ant colony optimization (ACO) is a heuristic technique for optimization that was introduced in the early 1990's [4]. ACO, which is inspired by the ants' foraging behavior, is very suitable for combinatorial optimization problem. A scientific description for ACO algorithm can be found in [5].

In this paper, we develop a method to correct the closed orbit using Rank-based Ant System (RAS) – a variant of ACO [6]. The goal is to apply correctors as few as possible while controlling the residual closed orbit within an acceptable level.

ERROR ESTIMATION AND BPMs LAYOUT OF HALS

The magnet elements of a storage ring can never be placed at their ideal positions. To simulate a real machine, we have to assume a statistical variation of their positions. The orbit distortion is caused by dipole errors which can be produced by bending magnets tilt, bending magnets strength or length error and transverse misalignment of quadrupoles etc. In addition, the orbit at quadrupoles or sextupoles concern with a closed orbit a lot in DLSR. If the closed orbit without correction exceed the vacuum chamber aperture limits, the orbit correction is impossible. Tracking the closed orbit with elegant [7] for 10,000 seeds, we find that the misalignment should be less than $8\,\mu m$ which is impossible technically. Tab. 1 shows the dipole error in the following simulations.

Table 1: Error Sheet for Magnets. All values are rms, and the truncation is 2σ.

dipole	misalignment	$5\,\mu$m
	rotation error	0.2mrad
	strength error	5×10^{-4}
quadrupole	misalignment	$5\,\mu$m
	strength error	10^{-3}
	multipole error	[8]
sextupole	misalignment	$5\,\mu$m
	strength error	10^{-2}
	multipole error	[8]

Once a closed orbit is established, the position of this closed orbit is measured by a large number of Beam Position Monitors (BPM) and small corrector magnets are used to correct the closed orbit towards the ideal orbit. There are several guildlines to place BPMs along the ring.

- BPMs should be spaced by 90° in phase advance.
- The orbit at light source points should be stable enough. So both sides of radiation elements must be measured by BPMs.
- Maximum position measured by BPMs (MAX-BPM) have to approximately equal to the maximum closed orbit distortion(MAX-COD).
- BPMs are close to the sextupoles. In theory, the dynamic aperture can be restored if the beam pass through the center of the sextupoles.

In accordance with the above principles, we place 17 BPMs per cell in HALS as shown in Fig. 1. We also compare MAX-BPM with the MAX-COD for 10,000 seeds in Fig. 2. From the figure, we know that there is 93% possibility at least when the tolerance is 10%. That is

$$P\left(\left|\frac{u_c - u_b}{u_c}\right| < 10\%\right) > 93\%, \qquad (1)$$

where u_c is MAX-COD and u_b is MAX-BPM. So our BPMs system is reasonable that the BPM measured value can reflect the real closed orbit.

ALGORITHM DESCRIPTION

Tab. 2 summarizes all elements contained in the HALS lattice cell. Every drift line is a possible position to place a corrector. Because the last drift is connected to the first line

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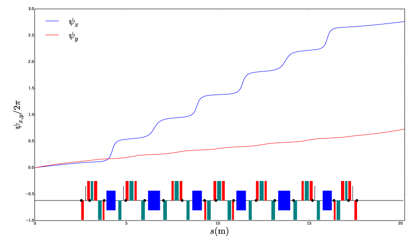
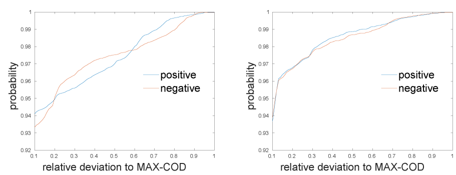


Figure 1: 17 BPMs' location in one cell. The blue and red lines are phase advance in horizontal and vertical plane respectively. The dark points on the baseline are where BPMs placed, The blue, red and cyan blocks are dipoles, quadrupoles and sextupoles respectively.



(a) Horizontal (b) Vertical

Figure 2: Probability of different tolerance. The blue and red lines are corresponding to positive and negative maximum closed orbit.

Table 2: All Elements Per Cell in HALS

defocussing combined dipoles	6
quadrupoles	20
sextupoles	19
octupoles	4
drifts	50

in the next cell, there are 49 optional locations for correctors. Except that the first location is chosen at the starting point in the first line, the rest locations are chosen at the midpoints of the drift lines. There are $2^{49} \approx 5.6 \times 10^{14}$ combinations in all. RAS is a powerful tool to deal with this situation. For convenient description, we number the locations from C_1 to C_{49}. We also mark C_0 as the origin where an artificial ant begins its trip and C_{50} as its destination. Every tour from C_0 to C_{50} indicates a correction scheme. The ant chooses its trajectory according to the pheromone left by the ant clony.

Initialize

Let e_{ij} be a edge from node C_i to C_j, and τ_{ij} be the pheromone on edge e_{ij}. The complete graph is composed by edges $e_{ij}(0 \le i < j \le 50)$. At the very beginning, all edges have the same pheromone

$$\tau_{ij} = \tau_0, \qquad (0 \le i < j \le 50). \tag{2}$$

Finish a Tour

When the ant is at the node i, the probability that node $j(j > i)$ is selected to be visited immediately can be written in the following formula:

$$p_{ij} = \frac{\tau_{ij}^{\alpha}}{\sum_{k=i+1}^{50} \tau_{ik}^{\alpha}}, i < j \le 50 \tag{3}$$

where α is a parameter to regulate the influence of τ_{ij}. This selection process is repeated until the ant arrives at the destination C_{50}. Then a new lattice file is generated based on the tour and we run elegant to perform the correction. The same seed is used in each correction. The optimization objective function is

$$u = \sqrt{u_{bx}^2 + u_{by}^2}, \tag{4}$$

where $u_{bx}(u_{by})$ is MAX-BPM of horizontal(vertical) plane.

Update Pheromone

After all M ants have generated a tour $\Omega_m(1 \le m \le M)$ and the corresponding correction have been done, the ants are sorted by optimization objective function in Eq. 4. Then $(\omega-1)$ elitist ants are considered to update pheromone. Additionally, the best solution until the current iteration is also taken into account. Expressed by formula as

$$u_* \le u_1 \le u_2 \le \ldots \le u_{\omega-1}. \tag{5}$$

The corresponding tours are $\Omega_*, \Omega_1, \ldots, \Omega_{\omega-1}$. Each tour appears in the elite group only once to avoid the danger of over-emphasized pheromone caused by many ants using the same paths.

The updating formula is

$$\tau_{ij}(n+1) = \rho\tau_{ij}(n) + \sum_{k=1}^{\omega-1}(\omega-k)\Delta\tau_{ij}^k + \omega\Delta\tau_{ij}^*, \tag{6}$$

$$\Delta\tau_{ij}^k = \begin{cases} \frac{Q}{u_k} & \text{if } e_{ij} \in \Omega_k \\ 0 & \text{otherwise} \end{cases} \quad \Delta\tau_{ij}^* = \begin{cases} \frac{Q}{u_*} & \text{if } e_{ij} \in \Omega_*, \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where n, ρ and Q are parameters of the current iteration, the pheromone reduction and the quantity of pheromone laid by an ant per tour respectively.

SIMULATION RESULT

All parameters mentioned in the previous section are listed in Tab. 3. The MAX-BPM described in Eq. (4) decreases with the increase of correctors as we excepted. The

Table 3: Parameters Used in the Simulation

τ_0	initial pheromone	10
α	influence of τ_{ij}	2.0
ρ	reduction of pheromone	0.8
Q	pheromone quantity laid by a ant	20
M	number of ants in the colony	20
ω	number of elite ants	6
ν	random search limit	49

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result is shown in Fig.(3). If the MAX-BPM is required to be less than the misalignments(5 μm in this case), 12 correctors at least are needed. When correctors are more than BPMs, a complete correction is possible for a reasonable scheme.

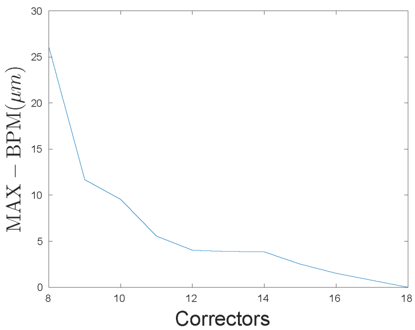


Figure 3: Best correction result for different number of correctors.

Figure 4 shows how the 12 correctors are placed. Figure 5 shows closed orbits before and after the correction using 130 sets of random errors. The corresponding statistical results of the maximum COD measured in the BPMs are shown in Fig. 6. It is clear that the maximum COD along the ring in x- and y-directions before the correction are bigger than 1mm which is the dynamic aperture of the bare lattice at $s = 0$. After the correction, the MAX-CODs along the ring are all smaller than 60 μm in x-direction, and 25μm in y-direction. Meanwhile, most MAX-BPMs are smaller than 5 μm which satisfies our requirment. So we can roughly say that the 12 corrector scheme works well in our case, but an exact estimation will have to be made upon dynamic tracking in the future. The maximum corrector strengths used in our correction does not exceed the corrector capacity which is about 1mrad.

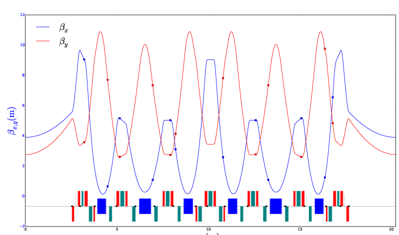
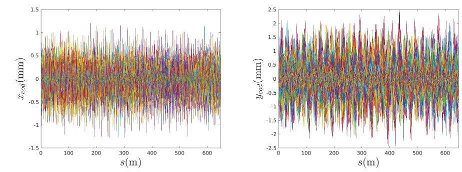


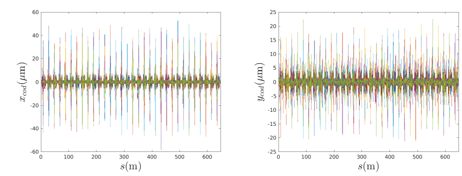
Figure 4: The 12 correctors scheme and β functions. All the 12 correctors are used to correct both horizontal and vertical directions. The abscisse of squares on β_x and β_y are where to place the correctors. Elements on baseline are the same with Fig. 1.

CONCLUSION

We explore the threshold of different kinds of dipole errors causing COD at first. To measure COD as accurate as possible, we propose a 17-BPMs layout scheme per cell in HALS and the simulation result also prove that it works well. Then we develop a method to correct the COD with different numbers of correctors. This method can find out a well worked correctors lawout of a fixed number (maybe not the best one). Our simulation result indicates that a 12 correctors correction scheme is suitable for the current HALS lattice. A dynamical tracking will be done in the future and the generic algorithm will be considered to replace the random search step for improving efficiency. Besides, the parameters used in Tab. 3 will be further optimized.

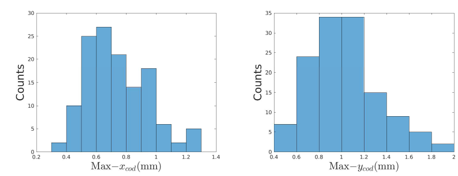


(a) Before correction,x_{cod} (b) Before correction,y_{cod}

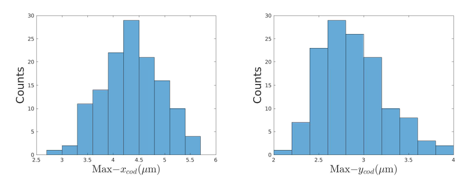


(c) After correction,x_{cod} (d) After correction,y_{cod}

Figure 5: COD along the storage ring before and after the 12 correctors scheme is applied. 130 sets of random error are used.



(a) Before, Max-x_{BPM} (b) Before, Max-y_{BPM}



(c) After, Max-x_{BPM} (d) After, Max-y_{BPM}

Figure 6: Counts of MAX-BPM before and after the 12 correctors scheme is applied. The same 130 sets of error are used.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research and Development Program of China (2016YFA0402000), the National Natural Science Foundation of China (11605203, 11475167), and the Chinese Universities Scientific Fund (WK2310000058).

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