Smoothing analysis of HLSII storage ring magnets *

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Abstract: Hefei Light Source (HLS) has been upgraded to improve the quality and stability of the synchrotron light, and the new facility is named HLSII. However, a final accurate adjustment is required to smooth the beam orbit after the initial instalment and alignment of the magnets. We implement a reliable smoothing method for the beam orbit of the HLSII storage ring. In addition to greatly smoothing and stabilizing the beam orbit, this method also doubles the work efficiency and significantly reduces the number of magnets adjusted and the range of the adjustments.

Keywords: smoothing, HLSII, curve fitting, least squares, iteration, relative error

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1 Introduction

Hefei Light Source (HLS) has been upgraded to improve the quality and stability of the synchrotron light since June 2010. The new light source is named HLSII. The stability of the beam in the storage ring requires the beam orbit to be continuous and smooth [1]. The magnets should therefore be adjusted accurately to smooth the beam orbit after installation and alignment. It is necessary for all the storage ring magnets to be placed with a high relative accuracy to meet the stringent demands of accelerator physics [2]. We also emphasize the work efficiency and propose many advanced approaches. Experience from other accelerators and synchrotrons all around the world suggests that smoothing analysis is a practical method considering both relative accuracy and work efficiency.

An averaging method based on the Root Mean Square (RMS) has been extensively studied in the general smoothing process. It has a drawback in terms of finding a smooth curve, and it deforms when the random errors decrease [3]. A low-pass filtering smoothing method has been studied in depth for the Pohang Light Source (PLS) storage ring in Korea. However, the smoothing method only reduces systematic errors, such as settlement and so on, but does not significantly reduce random errors [4]. In accelerator laboratories in the USA and Europe, fitting methods with Fourier series and spline functions have been widely studied, and these methods all need derivations of complex mathematical formulas and predefined functions [5]. This paper presents an attempt to develop a reliable and simple smoothing method based on the curve fitting of least squares and iteration by considering the structural characteristics of HLSII. The method takes into account random error and systemic error simultaneously, and has simple implementation and similar work efficiency to the low-pass filtering and spline function smoothing method.

2 Smoothing procedure

The storage ring of HLSII consists of 77 magnets, as listed in Table 1, and is located in a regular octagon as shown in Fig. 1 [6].

Table 1. Numbers of various magnets in the storage ring.

types of magnet	number
dipole	8
quadrupole	32
sextupole	32
undulator	5

The radius of the dipole is 2.7729 m and the angle between neighbouring dipole magnets is 45° [7]. A global coordinate system is built based on the geometrical symmetry, and the element coordinate system of every magnet is built according to its installation position. Each magnet is equipped with internal reference marks defined in its own coordinate system, and the centre of its own coordinate system is the magnetic field centre, as shown in Fig. 1.

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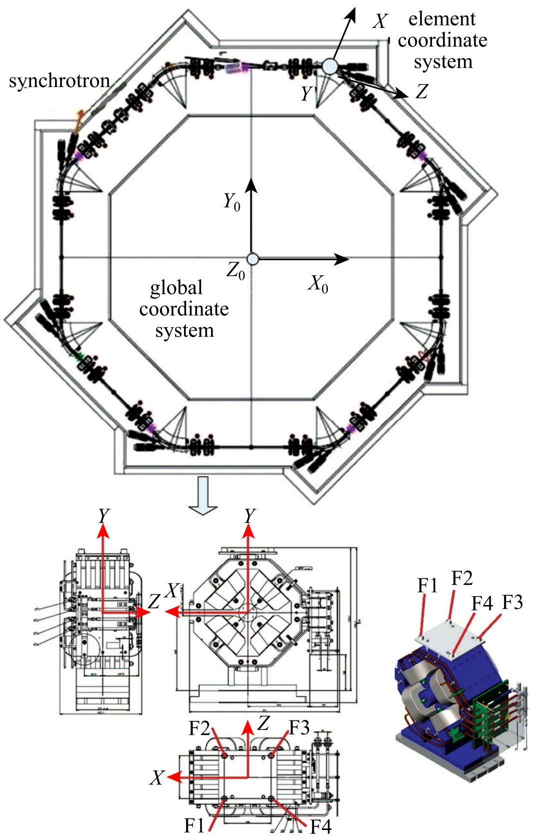

Fig. 1. (color online) Layout of all magnets in the HLSII storage ring.

2.1 Analysis

The orbit of the beam includes the longitudinal direction (Z axis) and transverse direction, and the transverse direction includes the horizontal direction (X axis) and vertical direction (Y axis), as shown in Fig. 1.

According to the closed orbit distortion formula (1) and the simulation code MAD developed by CERN, the effect of the alignment error of magnets can be studied [8].

$$(u_0^2(s))^{1/2} = \begin{cases} \dfrac{\beta(s)^{1/2}}{2\sqrt{2}\sin\pi\upsilon}\Delta u_{q,\mathrm{rms}}\sqrt{\Sigma\beta(KL_q)^2} \\ \dfrac{\beta(s)^{1/2}}{2\sqrt{2}\sin\pi\upsilon}[(\Delta B/B)_{b,\mathrm{rms}} or \Delta\phi_{b,\mathrm{rms}}]\sqrt{\Sigma\beta(L_b/\rho)^2} \end{cases}$$

In Eq. (1), $u_0(s)$ is the value of closed orbit distortion; $\beta(s)$ is the beta function at position s; K is the strength of the quadrupole; L_q is the length of the quadrupole; L_b is the length of the dipole; β is the beta function where the error occurs; ρ is the bending radius of the orbit; $\Delta u_{q,\mathrm{rms}}$ is the RMS displacement of all quadrupoles; and $\Delta\phi_{b,\mathrm{rms}}$ is the RMS angle error of all dipoles [9].

Studies have shown that the most significant closed orbit distortion is caused by the error of quadrupoles and sextupoles in the transverse directions and the error of rotation of the dipoles [10].

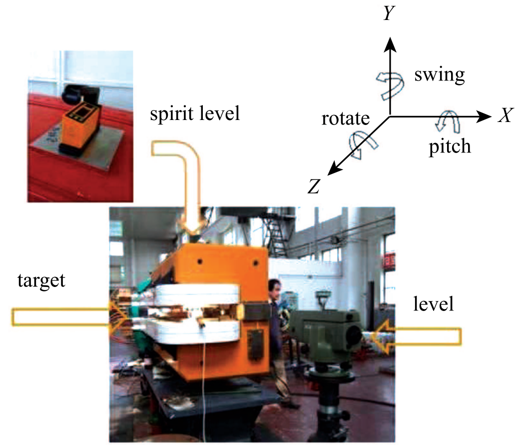

Fig. 2. (color online) Adjustment of the rotation of the dipole by spirit level.

The rotation of the dipole has an important effect on the closed orbit distortion. In order to decrease the rotation error of the dipole, a level and clamp were used to level the lower pole of the dipole during calibration of the dipole, as shown in Fig. 2, so that the upper pole of the dipole was also seen as level, ignoring manufacturing error. At the same time, a spirit level was placed on top of the dipole to measure the tilt value. During the installation process, a laser tracker was used to adjust the dipole, and the spirit level was used to check the tilt of the dipole. If the tilt value did not match the initial value, the dipole was adjusted to make the tilt value fit the initial one [11].

We consider the transverse directions (X axis and Y axis) rather than the longitudinal direction (Z axis) in the smoothing process because of the small effect of longitudinal direction on the closed orbit distortion. We also simplify the smoothing process by considering all magnets as points and neglecting their length and rotation.

2.2 Centre of magnets

The installation control network was established by adding many points based on the first control network. We placed these magnets to the storage ring based on the installation control network. Then a Leica LTD840 laser tracker (from Leica Geosystems, Switzerland), which has a ±10 μm+5 ppm measuring accuracy in the 2.5×5×10 m range, was used to align these magnets using the reference marks based on the installation control network.

After performing the alignment twice, we measured all the visible reference marks located on the outer surfaces of the magnets. By using the measured values of the reference marks, the magnetic field centre of the magnets can be obtained indirectly by backward analysis, which is based on coordinate transformation. Because the actual and theoretical positions of the reference marks do not match completely, the coordinate transformation is also based on least squares. Spatial Analyzer (SA) software can be used to process the least squares transformation by the best-fit function [12].

Few errors were found to exist among those magnets on comparing the actual positions with the theoretical positions. The statistical nature of installation errors appears to be a Gaussian distribution, where the aligned elements are randomly and normally distributed around this mean trend curve as shown in Fig. 3.

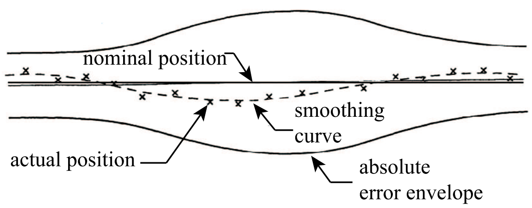

Fig. 3. Position of magnets with respect to theoretical orbit.

2.3 Smoothing based on the least squares polynomial

In the smoothing process, the mean square error method can be used to decide whether the magnets should be adjusted.

$$\delta=\sqrt{\frac{\sum_{i=1}^{n}a_i^2}{n}}. \tag{1}$$

In this formula, δ is the RMS, a_i is the difference between the actual and theoretical positions, and n is the number of magnets. In addition, it is necessary for each single deviation to be smaller than 2δ or 3δ[13].

We adjusted the magnets whose deviations were bigger than 2σ to guarantee the orbit smoothing. On the X axis, $\delta=0.082$ mm. Our data show that 17 magnets had deviations larger than 2σ and needed to be adjusted, and the average adjustment value was 0.12 mm. Meanwhile, nine magnets needed to be adjusted on the Y axis, and the average adjustment value was 0.09 mm, as shown in Fig. 4.

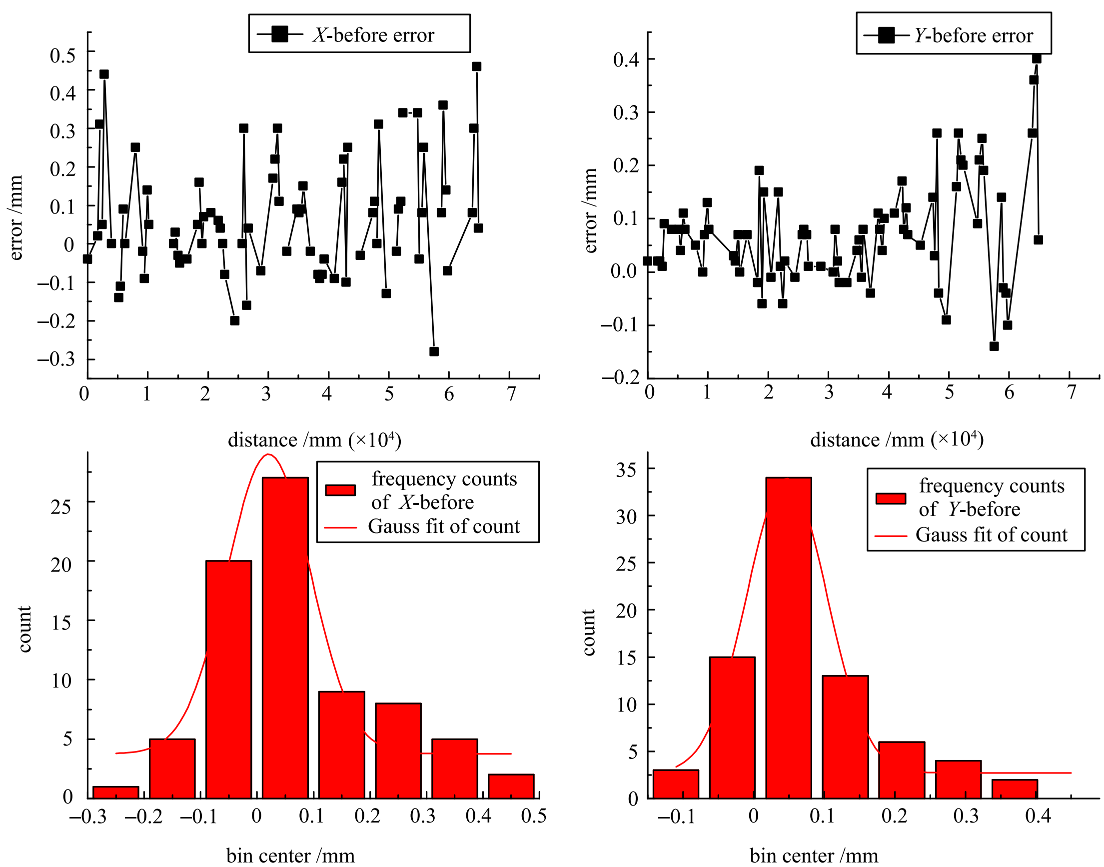

Fig. 4. Error distributions of mathematical statistics based on nominal orbit on the X and Y axes.

It is a concern that the number of magnets adjusted and range of adjustments are too high to implement the smoothing upgrade project. The offsets at the position of the magnets must be distributed to a new series at equal-spaced discrete points by interpolating with a cubic method in the low-pass filtering smoothing method. If we adopt the spline fitting method, we must analyze all error data to set some litter error points as fixed points before the smoothing analysis. Due to the structural characteristics of the HLSII storage ring, a smoothing method of least squares curve fitting and iteration was developed to reduce the number of magnets adjusted and achieve high work efficiency. The basic principles of the curve smoothing and bulldozer are quite similar. We smooth the downstream magnets by reference to the upstream smoothed magnets. The method has simpler implementation and similar work efficiency to the low-pass filtering and spline functions smoothing method.

There are two factors that need to be considered in this unique smoothing method: sliding windows and polynomials. The sliding windows include the length and acceptance threshold, as shown in Fig. 5.

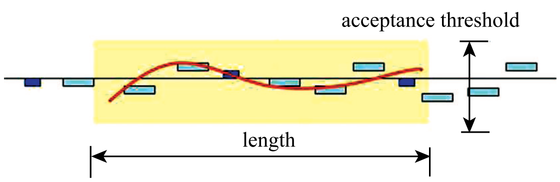

Fig. 5. Length and acceptance threshold of sliding windows.

The selection of length has a crucial effect on the work efficiency. Longer lengths indicate that higher-order polynomials are required to fit a smooth curve. Shorter lengths lead to low work efficiency as well. From the optimization simulation and analysis, it can be concluded that a length of eight or nine magnets is a good fit that balances the trade-off. Furthermore, the HLSII storage ring is a regular octagon, and each side has eight or nine magnets that equal the length of the windows. It is best that these magnets are smoothed in a straight line.

The acceptance threshold is still 2δ. δ could be obtained by the formula (2), but n is the number of magnets in the sliding windows. δ is different in every sliding window, according to Eq. (2).

Polynomial fitting based on the least squares method is a good candidate because least squares is one of the most reliable methods and is easy to implement using computer programs. If the order of the polynomial is greater than three, few magnets need to be aligned at the selected length. The beam current cannot cross through smoothly in such a high-order orbit. Third order is considered as a suitable order.

Iteration is also a key factor to keep the continuity of the smoothing orbit. To ensure the smoothing of the magnet orbits, the more common points the better. However, in this paper, half of their points in common balance the smoothing of magnets orbit and work efficiency.

In this paper, the centre of every magnet is obtained. The quadrupole located in the injection position of the storage ring is considered as the starting point, and then all magnets are located according to their positions relative to each other. First of all, the X axis is smoothed. The first sector of the octagon is considered as the first subsection, and then the sector next to it on one side is considered as the second subsection. The two subsections have half of their points in common as shown in Fig. 6. The other magnets are smoothed in the same way. δ can be obtained after the first smooth curve is fitted by least squares. The second smooth curve is fitted after the errors are adjusted. Other subsections are iterated according to the above method [14].

All these iteration steps for best-fitting can be executed by the MATLAB program, and these relative figures can also be obtained using the program.

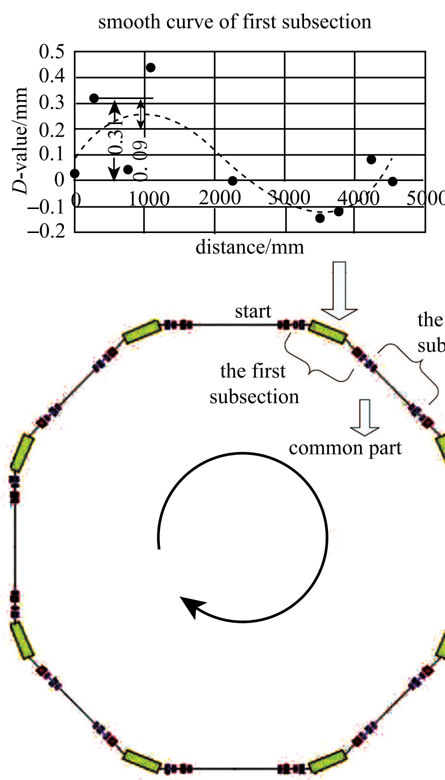

Fig. 6. (color online) Iterative curve-fitting of every subsection.

As shown in Fig. 6, the absolute error of the second point of the first subsection is 0.31 mm, which needs adjustment according to the traditional requirements. However, the relative error is just 0.09 mm relative to the smoothing curve, which should not be adjusted. The Y axis is also processed by the same method at the same time. The deviation of all magnets is smaller than 2σ by the end of the iterations.

3 Results

After the smoothing process, only 10 magnets needed to be adjusted and the average adjustment value was less than 0.05 mm on the X axis. The method greatly reduces the number of magnets adjusted and the average value of the adjustment. Only three magnets' Y values needed to be adjusted for smoothing when considering the level and spirit level. The smoothing results of the X and Y values are shown in Fig. 7.

The perimeter of the storage ring can be roughly obtained through estimating the centre point of the magnets. The design perimeter of the HLSII storage ring is about 66.1308 m. The actual perimeter calculated by the accelerator physics formula is:

$$C = \frac{c}{204.03M\mathrm{Hz}/45} = 66.1794 \text{ m}. \tag{2}$$

In Equation (3), C and c denote the perimeter of the ring and the speed of light respectively. The design perimeter and the actual perimeter are similar, so the smoothing result is validated [15].

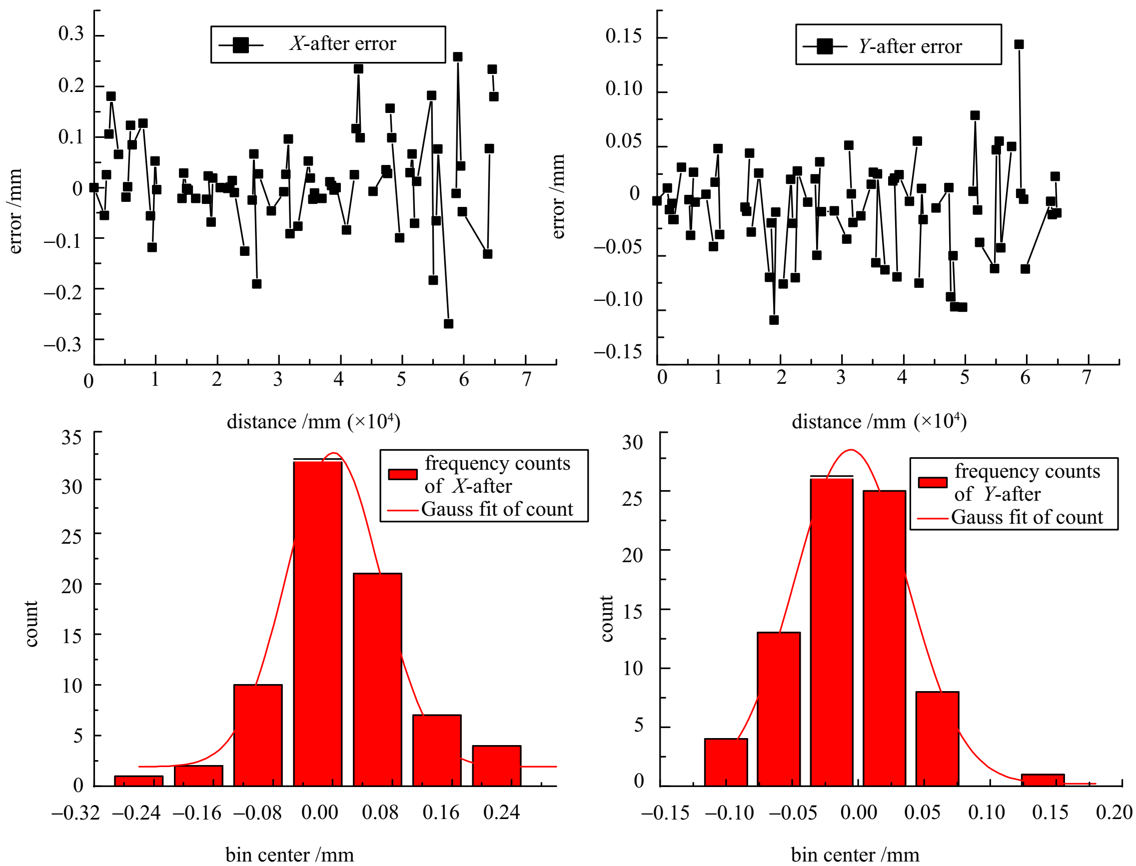

Fig. 7. Error distribution of mathematical statistics based on the smoothing orbit on the X and Y axes.

4 Conclusion

The smoothing method introduced in this paper is much better than previous methods for large scale particle accelerators. The acceptance threshold and length of windows and the polynomial order are different in different accelerators according to their structural characteristics. We have tested the method in the HLSII storage ring to establish its effectiveness for future accelerators. Its correctness and high efficiency have been proven in application to the HLSII. Specifically, this method doubles the work efficiency and significantly reduces the number of magnets adjusted and range of adjustment. In January 2014, the storage ring was successfully assembled and the beam orbit was smooth and stable.

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