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THE PRE-ALIGNMENT OF HIGH ENERGY PHOTON SOURCE STORAGE RING

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Abstract

In order to achieve 10 μm pre-alignment accuracy of storage ring in transverse and vertical, four laser trackers were used for set up a four-station μm measurement system. Experiment results show that the relative displacement measurement accuracy is better than 3 μm in 3-meter workpiece range, which can satisfy the real-time position feedback accuracy of the magnets in the process of ultra-high-precision pre-alignment. After two years of research and development, three pre-alignment standard workstations have been established. And the laser multilateration measurement method is adopted to the pre-alignment of the three, five and eight magnet girders in the storage ring of HEPS. Currently, 240 out of 288 girders have been pre-aligned after half a year of work.

INTRODUCTION

In order to improve the installation efficiency and accuracy of the storage ring for Chinese High Energy Photon Source (HEPS), each girder is usually pre-aligned in the laboratory, and then transported to the storage ring to participate in the tunnel alignment. Based on physical design of the accelerator, the standard deviation for the pre-alignment adjustment of magnets on one girder with respect to each other in transverse and vertical must below 10 μm.

In the particle accelerator field, laser tracker, such as the Leica AT930, is one of the most commonly used instruments for component fiducialization and alignment [1-3]. However due to the influence of the 15μm +6μm/m angle measurement accuracy, the three-dimensional coordinate measurement accuracy of the AT930 reaches 15μm +6μm/m. To improve its accuracy, numerous attempts have been made [2, 4]. However, these methods still cannot avoid the measurement of angle.

So, we build a four-station laser trackers multilateration measurement system for magnet pre-alignment. We first built a multilateration measurement system using four laser trackers. Then, the self-calibration of the system was completed by measuring more than 12 target points. Next, the front intersection is realized in combination with the Super-Cat's Eye, which realizes the real-time measurement of the coordinates of the magnet fiducial points. Finally, through careful adjustment, the pre-alignment of a girder with 8 magnets is completed, and the alignment standard deviation of transverse and vertical is within 6 μm.

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BASIC PRINCIPLE OF FOUR-STATION MULTILATERATION MEASUREMENT METHOD

The measurement principle of the multilateration measurement method mainly includes two parts: Self-calibration and Intersection measurement.

Self-calibration: The system parameters, that is, the coordinates of the four stations, are solved by measuring enough points.

Front intersection: Calculate the coordinates of the under-test point. After the system parameters are determined, four stations are used to measure the distance to the under-test point at the same time, and then the coordinate of the point can be calculated based on the distance.

There are four stations and n target point in the space, as shown in Fig. 1. Four stations were employed simultaneously to measure the distance to the target point. The center coordinate of the i-th station is $S_i = (X_i, Y_i, Z_i)$ $(= 1, 2, 3, 4)$ the coordinate of the j-th target point is $P_j = (X_j, Y_j, Z_j)$ $(j = 1, 2, 3, \ldots, n)$ the observed value between S_i and P_j is D_{ij}. The error equation group can be expressed as:

$$D_{ij} + v_{ij} = \sqrt{(X_i - x_j)^2 + (Y_i - y_j)^2 + (Z_i - z_j)^2} \quad (1)$$

where v_{ij} is the error corresponding to the observed value.

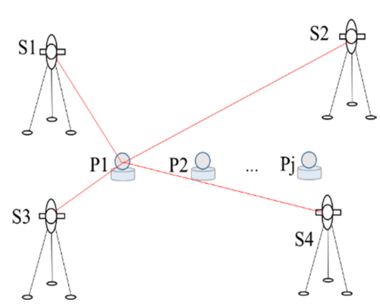

Figure 1: The principle of multilateration measurement method.

Expand Eq. (1) according to Taylor series and omit higher-order terms to obtain the error linear equation:

$$v_{ij} = f_{ij}\delta X_i + g_{ij}\delta Y_i + h_{ij}\delta Z_i - f_{ij}\delta x_i - g_{ij}\delta y_i - h_{ij}\delta z_i - \left(D_{ij} - D_{ij}^0\right) \quad (2)$$

As the self-calibration process was completed, the coordinate of the four stations S_i $(i = 1, 2, 3, 4)$ and the target points P_j $(j = 1, 2, 3, \ldots, n)$ were obtained in one coordinate system [5]. Then assuming that the coordinate of under-test points is $W\ (X, Y, Z)$, the measurement distance between the four stations and under-test point W is L_i $(i =$

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1,2,3,4). According to the principle of front intersection, the error equation for measurement distance is:

$$V_i + L_i = \sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2} \quad (3)$$

Equation (3) is a nonlinear equation, by linearizing and calculating the total differential, the error equation can be written as:

$$V = A\delta X - l \quad (4)$$

By solving the Eq. 4 according to the principle of adjustment, the coordinates of the under-test point can be obtained.

CONSTRUCTION OF MEASUREMENT SYSTEM

According to measuring principle, a four-station laser trackers multiliteration measurement system (FLTMMS) for pre-alignment of HEPS storage ring was built in the laboratory as shown in Fig. 2. Four LeicaAT930 laser trackers were used, and the reflection target was Leica Red Ring Reflection (RRR, self-calibration measurement) or Super-Cat's Eye (SCE, front intersection).

In the self-calibration process, the RRR is used as the reflection target placed on the target point to ensure the self-calibration accuracy. However, during magnet pre-alignment adjustment, the coordinates of the magnet fiducial points need to be obtained in real time through intersection measurement, so four laser trackers must measure a point at the same time. This requires the SCE as a measurement target because its acceptance angle is large enough.

The four AT930 are mounted on support columns. All support columns are filled with sand to improve the stability of the instrument. 8 target points are placed around the four stations. 32 points are magnet fiducial points. The remaining 8 target points are home-point.

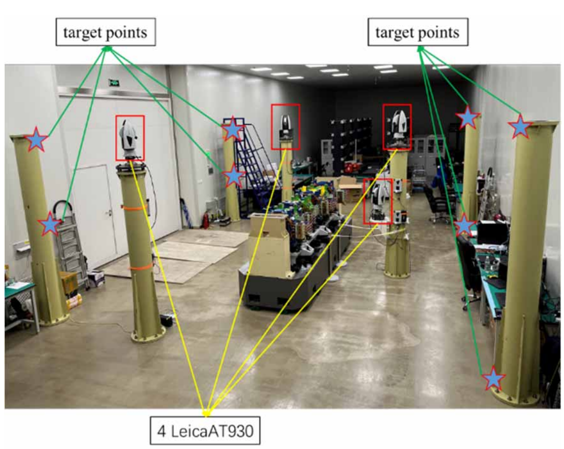

Figure 2: FLTMMS for pre-alignment of storage ring.

HIGH PRECISION PRE-ALIGNMENT WITH FLTMMS

The purpose of pre-alignment is to adjust the magnetic center of each magnet on the same girder to the theoretical position. The pre-alignment steps with FLTMMS are as follows:

First, self-calibration. In this step, the RRR is used as a reflection target. Four Leica AT930 trackers were used to measure more than 12 points (usually including 8 target points, 8 home points and 4 magnet fiducial points). Then, the system parameters are obtained through the adjustment solution.

Second, dynamic adjustment. The real-time deviation between the actual coordinate and the theoretical coordinate of the magnet fiducial points is obtained by front intersection. The adjustment process will stop when the deviation between the actual coordinate and the theoretical coordinate is less than 10 µm.

Third, locking. The magnet is firmly fixed on the girder by the locking mechanism after the dynamic adjustment process is complete. During the locking process, it is necessary to ensure that the deviation between the actual coordinate and the theoretical coordinate is within 10µm, so it is also necessary to use the SCE to monitor the magnet fiducial points in real time.

Finally, the pre-alignment of a girder with eight magnets was finished using the FLTMMS, the results are shown in Table 1. After pre-alignment, the *X* (transverse) direction deviation of the eight magnets is less than 10 µm, the *Y* (vertical) direction deviation is less than 14 µm. The standard deviations are less than 4 µm (transverse), 6 µm (vertical), respectively, which meets the accuracy requirements of HEPS pre-alignment.

Table 1: Results After Pre-Alignment

Fiducial Points	DX	DY	Fiducial Points	DX	DY
QD3F1	-0.001	0.009	SF1F1	0.005	0.010
QD3F2	-0.005	0.002	SF1F2	0.005	-0.011
QD3F3	-0.005	0.003	SF1F3	0.005	0.006
QD3F4	-0.001	-0.003	SF1F4	0.005	-0.004
SD2F1	0.001	0.001	ABF1F1	-0.010	0.001
SD2F2	-0.003	-0.014	ABF1F2	-0.002	0.004
SD2F3	-0.003	0.004	ABF1F3	-0.002	0.006
SD2F4	0.001	-0.011	ABF1F4	-0.010	0.006
OCT1F1	0.004	0.000	SD1F1	-0.002	-0.002
OCT1F2	0.000	-0.006	SD1F2	-0.001	-0.004
OCT1F3	0.000	0.007	SD1F3	-0.001	0.005
OCT1F4	0.004	0.007	SD1F4	-0.002	-0.006
QF2F1	0.000	0.004	QD2F1	-0.002	-0.002
QF2F2	0.008	0.006	QD2F2	0.002	0.002
QF2F3	0.008	-0.006	QD2F3	0.002	-0.002
QF2F4	0.000	-0.007	QD2F4	-0.002	-0.003
Standard Deviation	0.004	0.006			

CONCLUSION

In conclusion, a laser tracker-based multilateration method has been developed for the magnet pre-alignment

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of HEPS storage ring. The multilateration system has been built in laboratory. It successfully achieved absolute position measurement accuracy of 7.1 µm and relative displacement measurement accuracy of 3 µm in a 4 m×1.2 m×1.5 m volume. After adjustment, a pre-alignment accuracy of 6 µm for HEPS magnets has been achieved. Currently, 240 out of 288 girders have been pre-aligned after half a year of work. The alignment accuracy of the multilateration system can still be improved by increasing the height difference of four stations. Furthermore, this laser tracker-based multi-lateration method can be applied to other high precision fields, for example, the field of industrial measurement.

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