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PROPOSAL OF AN ALIGNMENT SYSTEM FOR HALF: THE REFERENCE NETWORK OF ALIGNMENT

Xiao Li, Xiaoye He#, Zhaoyi Wang, Wei Wang, Tao Luo[1], Jiaxin Chen[1]
National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, People's Republic of China
[1]also at Institute of High Energy Physics, Chinese Academy of Science (CAS), Beijing, People's Republic of China

Abstract

As a fourth-generation light source based on the diffraction-limited storage ring, Hefei Advanced Light Facility (HALF) has higher requirements for magnets alignment in accuracy, efficiency and reliability. In this paper, the Reference Network of Alignment (RNA) system is proposed to improve the magnetic axis alignment accuracy on the radial direction of the beamline. Herein, we mainly introduce the concept design and the theoretical analysis of the RNA system, which center on the novel fusion method of sensors. A simulation result shows that it is credible to assume the RNA system can achieve an alignment installation accuracy of 20 μm and a displacement monitoring accuracy of 10 μm.

INTRODUCTION

Hefei Advanced Light Facility (HALF), developed by the National Synchrotron Radiation Laboratory (NSRL) of the University of Science and Technology of China (USTC), is a fourth-generation vacuum ultraviolet and soft X-ray light source based on the diffraction-limited storage ring. It has crucial requirements for both the accuracy and efficiency of alignment [1-3].

The Reference Network of Alignment (RNA) system, as an innovative alignment technology based on a combination of multi-sensors, is proposed. It uses a girder assembly with several magnets after fiducialization and pre-alignment as the independent unit, and a long stretched wire as a straightness reference. Numerous pairs of wire position sensors (WPSs) for which the positions and orientations have been known according to each other to position the girder assembly with respect to a stretched wire. In order to strengthen the determinism of the RNA system, hydrostatic levelling sensors (HLSs) and two-axis inclination sensors (TILTs) are added. The RNA system directly associates the magnetic axis with the reference wire to improve the accuracy and efficiency of alignment feasibly. And this method is advantageous because it not only can be applied to the alignment of magnets with a higher precision, but can also meet high-accuracy position monitoring of the dynamic displacement of the magnetic axis in real-time.

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# xyhe@ustc.edu.cn

CONCEPTUAL DESIGN

The RNA system consists of several girders assembly each of which is the independent unit for alignment, and a long stretched wire as a straightness reference. In order to facilitate the alignment process, several magnets are pre-aligned on a common girder assembly. Once the support assembly is transferred into the tunnel, it can be aligned as a whole. The relationships between the magnetic axis of girder assembly and straightness reference are measured by independent sensors that positions and orientations have been known according to each other. Once the girders are aligned with respect to the same reference, all of magnetic axes should fall within a cylinder with a radius of several micrometers.

We propose the concept of the base-plate on which the sensors are fixed to determine the relative position and orientations of sensors. Its structure is shown in Fig. 1. Sensors in the base-plate include the WPS (oWPS), the HLS sensor and the Nivel sensor as a type of TILT. WPS can observe the stretched wire with a micrometric accuracy in the vertical and horizontal directions [4, 5]. The WPS coordinate system is established by three balls interface [6], as shown in Fig. 2. HLS improves the redundant observations in the vertical direction. Figure 3 shows how to establish the HLS coordinate system. The Nivel sensor is a two-axis high precision inclination sensor for the simultaneous measurement of inclination and the direction of inclination of the base-plate. The overall design of the RNA system is shown in Fig. 4.

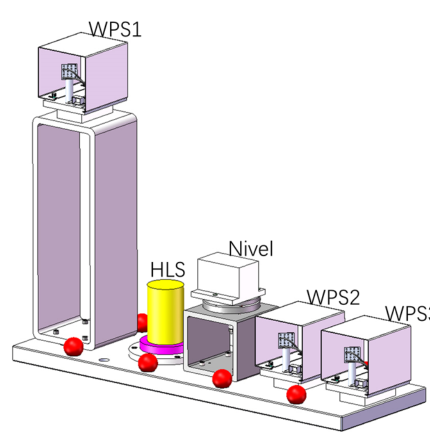

Figure 1: The construction of the base-plate.

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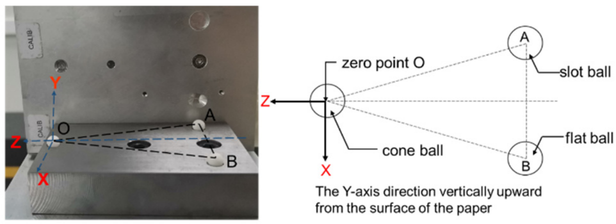

Figure 2: The construction of the WPS coordinate system.

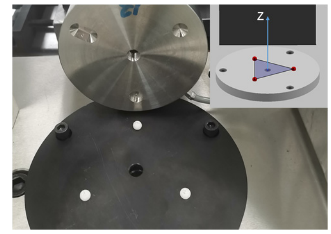

Figure 3: The construction of the HLS coordinate system.

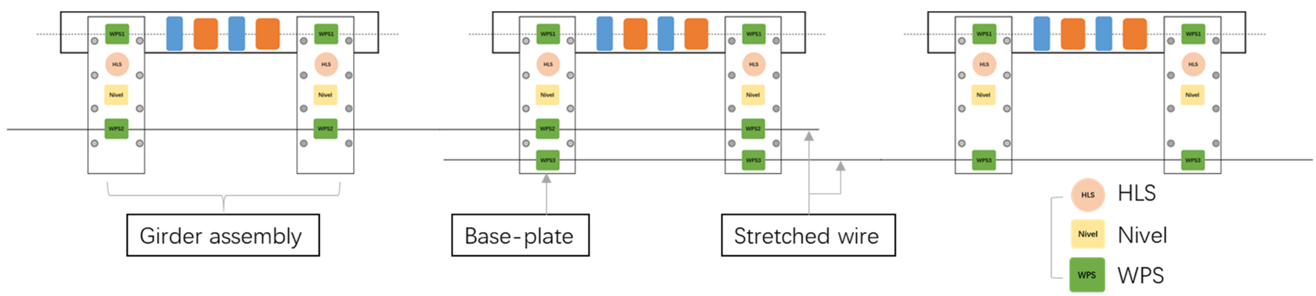

Figure 4: The overall design of the RNA system.

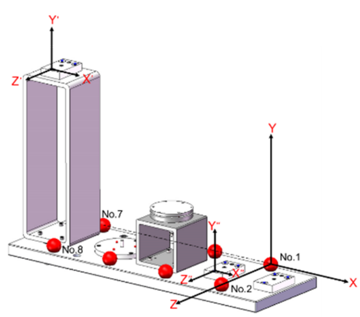

Figure 5: The coordinate systems in base-plate.

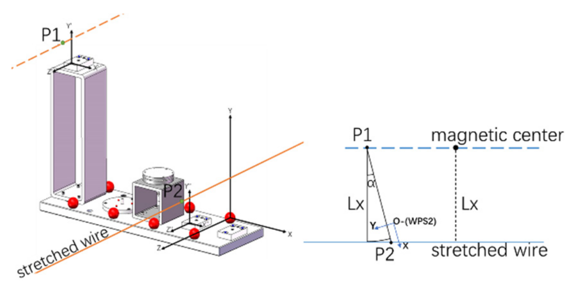

Figure 6: The schematic diagram for coordinate transformation.

THEORETICAL ANALYSIS

Theoretical Analysis of the RNA System during the Procedure of Alignment Installation

On-site alignment aims to align all magnetic axes in the form of a cylinder with a radius of a few micrometers, based on a stretched wire. Before that, the base-plates have been calibrated in USTC using a CMM with an uncertainty of 3 μm (σ). According to the rules for establishing the coordinate system for the base-plate and sensors described above, all of the coordinate systems are established and displayed in Fig. 5. Further, the vibrating wire technique accomplished the pre-alignment with a precision of 10 μm in NSRL [7]. This is advantageous for the RNA system, because the wire can be easily observed and written in data through the WPS.

Once the girders assembly are transferred to the tunnel. The RNA system will align the magnetic axes with higher precision based on the transformation among the coordinate systems. Let point P1 be a point on the vibrating wire observed by WPS1, P2 be a point on the stretched wire observed by WPS2. Then the transformation process can be divided into two steps: First, we transform the coordinates of P1 from the WPS1 coordinate system to the WPS2 coordinate system using a Bursa Model of coordinate transformation as shown in Eq. (1) [8, 9]. Furthermore, we can then use Eq. (2) to transform the coordinates of P1 to the coordinates of P2 in the WPS2 coordinate system used to position the girder assembly $[L_Y, L_Y, L_Z]^T$ is the distances between the magnetic axis and the stretched wire we set. As shown in Fig. 6, α and β are angles between the X-axes and Y-axes of the magnet coordinate system and the WPS2 coordinate system

$$\begin{bmatrix} X_{P1-WPS2} \\ Y_{P1-WPS2} \\ Z_{P1-WPS2} \end{bmatrix} = \lambda \cdot R_{12} \cdot \begin{bmatrix} X_{P1-WPS1} \\ Y_{P1-WPS1} \\ Z_{P1-WPS1} \end{bmatrix} + \begin{bmatrix} \Delta X_{12} \\ \Delta Y_{12} \\ \Delta Z_{12} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} X_{P2-WPS2} \\ Y_{P2-WPS2} \\ Z_{P2-WPS2} \end{bmatrix} = \begin{bmatrix} X_{P1-WPS2} \\ Y_{P1-WPS2} \\ Z_{P1-WPS2} \end{bmatrix} + \begin{bmatrix} Lx \\ Ly \\ Lz \end{bmatrix} + \begin{bmatrix} 1-\cos\alpha & 0 & 0 \\ 0 & 1-\cos\beta & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Lx \\ Lx \\ Lx \end{bmatrix}, \quad (2)$$

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Theoretical Analysis of the RNA System during the Procedure of the Real-Time Monitoring

All three sensors are combined to carry out the deformation analysis during the operation of accelerator, to receive the high-accuracy position deviation monitoring of magnetic axis in real-time based on the stretched wire and the hydrostatic surface. This can be expressed as in Eq. (3)

$$\begin{cases} \begin{bmatrix} X'_{P2-WPS2} \\ Y'_{P2-WPS2} \\ 0 \end{bmatrix}^{T} = R \cdot \begin{bmatrix} X_{P2-WPS2} + \Delta x_2{}' \\ Y_{P2-WPS2} + \Delta y_2{}' \\ 0 \end{bmatrix}, \\ H_2 = H_1 + \Delta y_2{}' \end{cases} \quad (3)$$

where $(X_{P2-WPS2}, Y_{P2-WPS2})$, (H_1) are the values of WPS2 and HLS measurements at the moment of installation end, while $(X'_{P2-WPS2}, Y'_{P2-WPS2})$, (H'_1), are the real-time data. R represents the rotation matrix of the WPS2 coordinate system between the end of the installation process and the instant of monitoring, which can be observed using the Nivel sensor.

ACCURACY ESTIMATION

Since the application of the RNA system consists of several steps between alignmnet and monitoring. We modeled and simulated the alignment errors in the RNA system in the alignment and the monitoring processes using the Monte Carlo method of distribution propagation, as implemented in MATLAB. The error distribution curve shows that, the mean of the installation errors was 10.15 μm, and the probability that the error was less than 20 μm was 97.9%, as shown in Fig. 7. The mean value of the monitoring errors was 5.38 μm, and the relative probability of these being less than 10 μm was 92.7%, as shown in Fig. 8.

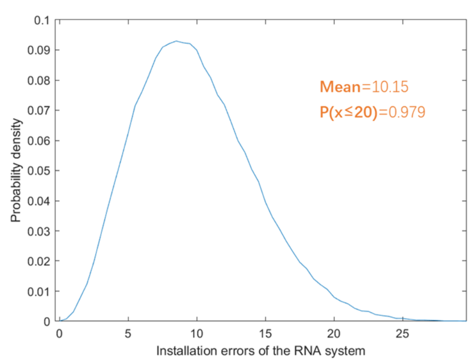

Figure 7: Monte Carlo simulation of the installation process, with 200,000 points.

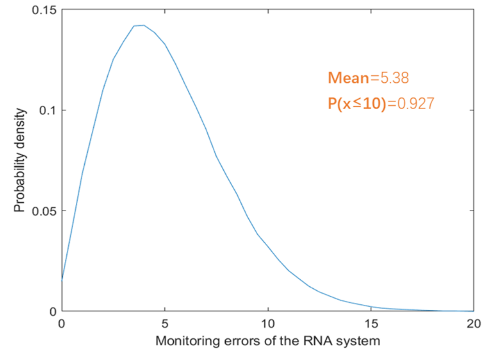

Figure 8: 200000 times Monte-Carlo simulations of the monitoring process.

CONCLUSION

This paper has presented the conceptual design and a theoretical analysis of an RNA system, a novel technology for improving both the accuracy and efficiency of alignment. First, the conceptual design of the RNA was described, several girders assembly and a stretched wire form the RNA system. And a concept of the base-plate was proposed to determine the relative position and orientations of the sensors by calibration. Based on that, We then carried out the elementary theoretical analysis of the RNA system during the procedure of alignment and monitoring, which confirms the theory feasibility of the RNA system, and provided a sufficient theoretical basis for the subsequent debugging and application of the RNA system. According to the simulation results, the probability of the error being less than 20 μm in the process of the installation was 97.9%, and the probability of the error in the monitoring phase being less than 10 μm was 92.7%. These results are close to the targets proposed for the RNA system.

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