Preliminary R&D of vibrating wire alignment technique for HEPS

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Abstract: The alignment tolerance of multipoles on a girder is better than ±30 μm in the storage ring of the High Energy Photon Source (HEPS) which will be the next project at IHEP (Institute of High Energy Physics). It is difficult to meet the precision when only using the traditional optical survey method. In order to achieve this goal, a vibrating wire alignment technique with high precision and sensitivity is considered to be used in this project. This paper presents some preliminary research works about theory, scheme design and achievements.

Key words: vibrating wire, alignment, magnetic field measurement, accelerator, magnet

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1 Introduction

HEPS will be a 6 GeV, 1296 m circumference third generation synchrotron radiation facility with ultra emittance and extremely high brightness. The emittance will be better than 0.1 nm·rad. The storage ring is a 48 cell 7BA lattice. Fig. 1 is one of 48 typical cells. The multipole girder that supports several quadrupoles and sextuples is designed to be 3.8 meters, but this is not the final value, as the lattice is still in design [1].

Table 1 shows the alignment tolerance in HEPS. It is difficult to achieve the required accuracy using the traditional optical survey. So the vibrating wire alignment technique is considered to meet the tolerance of ±0.03 mm between magnet to magnet on one multipole girder. Besides, automatic adjustment of the girder can help to achieve a tolerance of ±0.05 mm between girders.

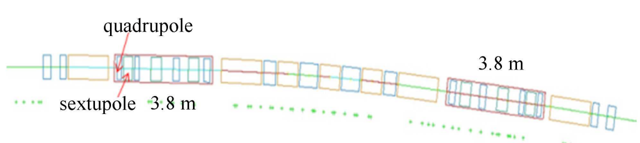

Fig. 1. (color online) One of 48 typical cells.

The vibrating wire technique has been used in some different projects in many labs. It has demonstrated the potential to measure the magnetic center to the required accuracy. These applications of vibrating wire are based on the same fundamental principle, but the specific purposes are distinct. The vibrating wire was first used at Cornell University to find the magnetic center of superconducting quadrupoles placed inside the cryostat for CESR [2]. Later, it was used to find the solenoid magnetic center [3] and study the characterization of undulator magnets [4]. In SLAC, this technique is used to fiducialize the quadrupoles between undulator segments for LCLS [5] and align the quadrupole for FFTB. At CERN, its application is solenoid magnetic center finding [6]. At PSI, vibrating wire is used to find the magnetic axis of quadrupoles for Swiss Free Electron Laser [7]. At BNL, this technique is used to align the quadrupoles and sextupoles on one girder for NSLS-II [8].

Table 1. HEPS alignment tolerance.

tolerances	magnet to magnet	girder to girder
horizontal	±0.03 mm	±0.05 mm
vertical	±0.03 mm	±0.05 mm
beam direction	±0.5 mm	±0.5 mm
roll angle	±0.2 mrad	±0.2 mrad

Vibrating wire is based on measurement of the magnetic axis to align the magnets. It is a further evolution of the pulsed wire method. A simple diagrammatic sketch is shown in Fig. 2 [9]. The specific principle of this method is: a single conducting wire is stretched through the magnet aperture and driven by an alternating current. Transversal vibrations are continuously excited by periodic Lorentz Force. By matching current frequency to one of the resonant modes of the wire, the vibration amplitude and sensitivity are enhanced and the magnetic induction intensity at the wire position can be calculated. Moving the wire across the aperture in the horizontal direction (x) or vertical (y) direction, the magnetic induction intensity distribution can be obtained and the magnetic axis can be found.

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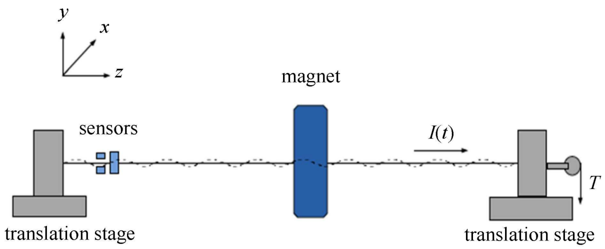

Fig. 2. (color online) Diagrammatic sketch of vibrating wire.

2 Research development

So far, the main research development is related to research work on theory and scheme design, including derivation of basic theory, design of the test bench model, design of the sag measurement scheme, calculation of vibrating amplitudes, design of the sensor circuit and sensor calibration and design of the data acquisition and control system.

2.1 Basic theory

According to Newton's law, the differential equation of the motion of a section of wire dz in the y-z plane (Fig. 3) is:

$$\mu\frac{\partial^2 y}{\partial t^2}=T\frac{\partial^2 y}{\partial z^2}-\mu g-\gamma\frac{\partial y}{\partial t}+B_x(z)I(t), \tag{1}$$

with μ the mass per unit length, T the wire tension, $\mu\cdot g$ the gravity, and γ the damping coefficient. $I(t)$ is the current in the wire, it depends on time as $I(t)=I_0\exp(\mathrm{i}\omega t)$. $B_x(z)$ is the horizontal magnetic field. Solving the differential equation, the homogenous solution is:

$$y_{\mathrm{h}}(z,t) = \mathrm{Re}\sum_{n=1}^{\infty}\sin\left(\frac{n\pi}{l}z\right)\left[A\mathrm{e}^{-\frac{\alpha}{2}t}\cos\sqrt{\omega_n^2-\left(\frac{\alpha}{2}\right)^2}t\right. \\ \left.+B\mathrm{e}^{-\frac{\alpha}{2}t}\sin\sqrt{\omega_n^2-\left(\frac{\alpha}{2}\right)^2 t)}\right], \tag{2}$$

with $\alpha=\gamma/\mu$, $\omega_n^2=(T/\mu)\ (n\pi/l)^2$, l wire length, A and B arbitrary complex constants, and Re representing the real part of the expression.

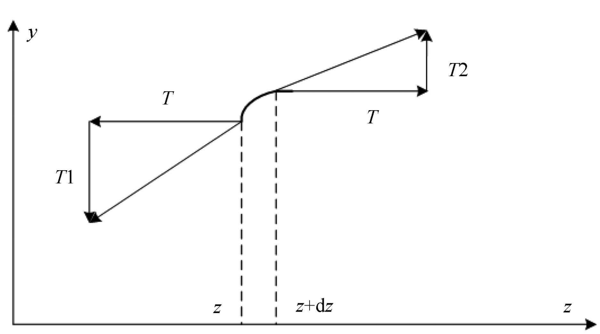

Fig. 3. Force analysis of a section of wire dz.

The particular solution due to gravity is:

$$y_{\mathrm{g}}(z)=\frac{\mu g}{2T}z(z-l)=\frac{g}{8f_1^2l^2}z(z-l), \tag{3}$$

where f_1 is the wire fundamental frequency.

The particular solution due to the Lorentz force is:

$$y_{\mathrm{d}}(z,t)=\mathrm{Re}\sum_{n=1}^{\infty}\frac{-I_0B_{xn}}{\mu(\omega^2-\omega_n^2-\mathrm{i}\omega\alpha)}\sin\left(\frac{n\pi z}{l}\right)\exp(\mathrm{i}\omega t), \tag{4}$$

where

$$B_{xn}=\frac{2}{l}\int B_x(z)\sin\left(\frac{n\pi z}{l}\right)\mathrm{d}z. \tag{5}$$

2.2 Vibrating wire test bench model

Figure 4 is the design of the vibrating wire test bench model. The whole test bench is composed of two parts which are the end bench and the magnet support girder. The difference between the fixed end bench and the free end bench is the fixed way of the wire. At the fixed end, the wire is fixed and located by a V notch. At the free end, the wire is pulled by weights through a pulley and also located by a V notch. On each end bench, there are two translation stages and two sensors. The horizontal stage moves wire in the x direction and the vertical one for wire movement in the y direction. The horizontal sensor detects the wire vibration amplitudes in the x direction and the vertical one in the y direction. The vibrating wire is 0.125 mm diameter wire made with copper-beryllium alloy. The magnet support girder is designed to be 5.4 m. Two parallel guideways are installed above the girder in order to move magnets conveniently. By moving magnets along the guideways, the magnetic center could be detected in different places along the girder. The quadrupole and sextupole are borrowed from BEPC II for lack of magnets made for HEPS. They are 105Q and 130S.

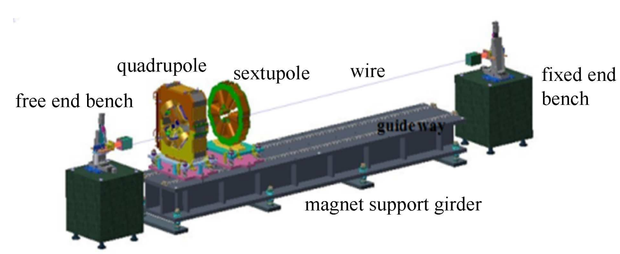

Fig. 4. (color online) Vibrating wire test bench model.

2.3 Sag measurement scheme

For a 7 m long wire, sag is unavoidable because of self-weight. It is about several hundred microns. To find the vertical magnetic center, accurate sag correction is essential. Fig. 5 shows the sag measurement scheme.

The method is to establish a coordinate system relative to the wire and then measure the sag at different places along the wire (z direction). A laser tracker and electronic gradienter Leica NIVEL200 are used to adjust the position and orientation of the sensor. The sensor is placed in different locations and used to measure the vertical position of the wire.

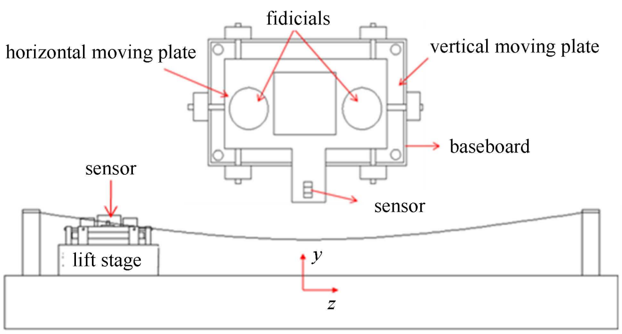

Fig. 5. Sag measurement scheme.

2.4 Sensor circuit and calibration

The product model of the sensor in HEPS is SHARP GP1S094HCZ0F which is a photointerrupter with opposing emitter and detector in a molding that provides non-contact sensing. The function of the sensor is to detect the vibrating amplitudes $y_\mathrm{d}(z,t)$ change over time due to Lorentz Force. Because the sensor is just a simple electron component, the sensor circuit is designed to make the output voltage appropriate.

We perform the sensor calibration on the sensor output test bench (Fig. 6). By changing the position of the sensor relative to the wire on the sensor output test bench, a series of points which are the output voltages were obtained. Because the sensor received different optical signals when the wire is at different locations, the output voltages are different. Figs. 7 and 8 are the outputs of one of four sensors that were tested. The results are summarized in Tables 2 and 3. There are two linear output parts. In each part, the wire displacement is about 0.1–0.12 mm. One part will be chosen as the workspace. There was little difference in the output voltages between covering the sensor with a light shield and exposing the sensor in the lab light. However, the voltages were more stable when the sensor was covered. The sensitivity of the sensor is approximately 30 mV/μm. In one test position, the measures of variation reduced from 20 mV to 6 mV after filtering. The stability has improved significantly. So adding filters to the circuit and DAQ program is under consideration.

Table 2. Shading voltages of sensor.

	left linear region		right linear region	
voltages/V	9.45	5.8	5.58	9.27
voltage difference/V	3.65		3.69	
displacement/mm	0.18	0.3	0.38	0.5
displacement difference/mm	0.12		0.12	
voltage/displacement/(mV/μm)	30.42		30.75	

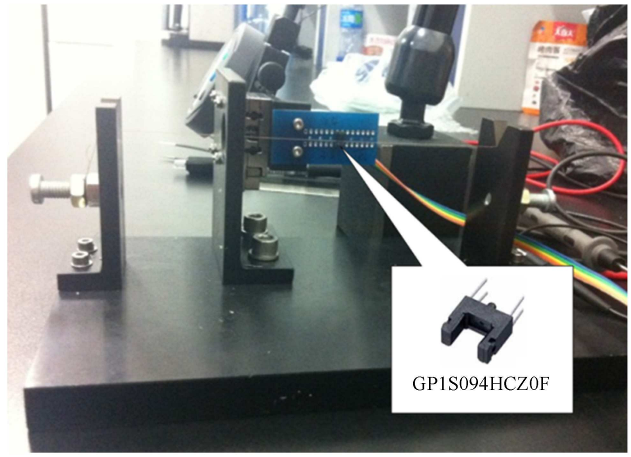

Fig. 6. (color online) Sensor output test bench.

Table 3. No shading voltages of sensor.

	left linear region		right linear region	
voltages/V	9.1	6	5.56	9.27
voltage difference/V	3.1		3.71	
displacement/mm	0.2	0.3	0.38	0.5
displacement difference/mm	0.1		0.12	
voltage/displacement/(mV/μm)	31		30.92	

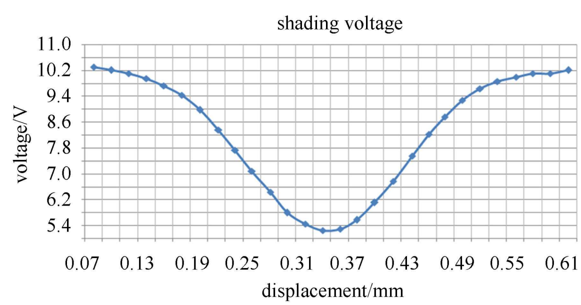

Fig. 7. (color online) Shading voltage of sensor.

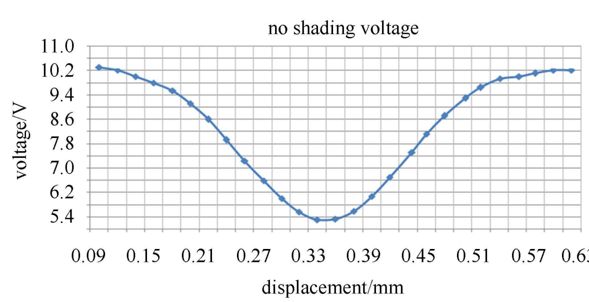

Fig. 8. (color online) No shading voltages of sensor.

2.5 Calculation of vibrating amplitudes

Vibration amplitudes should be controlled within the voltage linear output part, and it also should make full use of this region. According to the measurement, the linear region width is about 0.1–0.12 mm. We designed the wire vibration amplitudes to be 0.045 mm.

According to Eq. (4), the equation of measurement of a quadrupole magnetic center is deduced:

$$y_{\max}(z)=\left[\frac{I_0 2Gl_{\rm Q}}{\mu\omega_n\alpha l}\sin\left(\frac{n\pi}{j}\right)\sin\left(\frac{n\pi z}{l}\right)\right]|\Delta y|. \quad (6)$$

We measure the sextupole magnetic center using Eq. (7).

$$y_{\max}(z)=\left[\frac{I_0 B''l_{\rm Q}}{\mu\omega_n\alpha l}\sin\left(\frac{n\pi}{j}\right)\sin\left(\frac{n\pi z}{l}\right)\right](\Delta x^2+\Delta y^2). \quad (7)$$

I_0 is the wire current amplitude. $Gl_{\rm Q}$ is the quadrupole integrated gradient. $l_{\rm Q}$ is the quadrupole length. n is the resonance order. ω_n is the harmonic frequency. α is the damping constant. J equals $l/z_{\rm magnet}$. $z_{\rm magnet}$ is the location of the magnet along the wire. $B''l_{\rm Q}$ is the sextupole integrated gradient. Δy is the distance between magnetic center relative to the wire in the y direction and Δx is the distance between magnetic center relative to the wire in the x direction.

In short, according to the distance between the magnetic center and wire, the distance between wire end and magnet, the distance between wire end and sensor, and magnetic field gradient, the AC current can be calculated. We use this method to estimate the AC current in the wire according to the previous magnetic survey datum of the magnets borrowed from BEPCⅡ.

2.6 Data acquisition and control system

Figure 9 is the scheme of the data acquisition and control system. There are four input signal ranges in DAQ card PXI-6122. The sampling rate is 500 Ks/s per channel. Its function is to sample 2 sensors and 1 driving current signals simultaneously. Data will be transported to the IPC by the communication cards PXIe- 8360 and PCIe-8362. IPC also controls the movement of 2 x-y stages. We use LabVIEW software to do data acquisition and data processing.

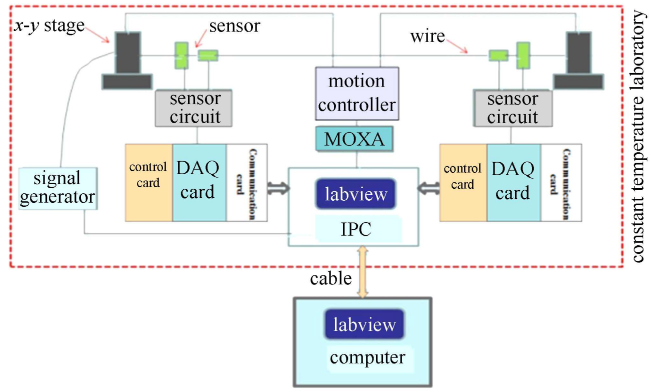

Fig. 9. (color online) Scheme of data acquisition and control system.

3 Conclusions

The alignment tolerance of multipoles on a long girder in HEPS should be better than 30 microns. The vibrating wire alignment technique is appropriate to achieve the required accuracy. This technique has never previously been used in China. Many research studies have been done to study the technique. In this article, we introduced the background of the magnets alignment in HEPS and preliminary research work and achievements.

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