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Stretch-wire system for integral magnetic field measurements☆

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Abstract

A stretch-wire system was developed to measure and characterize the first and second magnetic fields integral of insertion devices and the harmonic field components of lattice magnet. This simple wire support structure was built with a reliable high precision, and high-speed automatic measurement system for measuring the transversal field integrals of various kind magnets. The measurement precision of the system is 1.5 G cm (70 G cm^2) for the first (second) field integral of the insertion devices and 0.01% for the harmonic field components analysis of the lattice magnets. The scanning time for a complete measurement is five minutes for the first and second field integral distribution, and four minutes for the harmonic field components.

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Keywords: Insertion devices; Hall probe; Stretch-wire; Magnetic field measurement

1. Introduction

The stretch-wire measurement system performs several functions: (1) measuring the first and second field integral of various magnets, such as individual magnet blocks and insertion device magnets; (2) measuring harmonic field components of insertion devices and lattice magnets in the storage ring; and (3) double check the integral field measurement results obtained by Hall probe measurement. The feature of the system is that the measurement speed of the field integral is markedly beyond 10 times faster and with higher precision than that of a three-dimensional Hall probes measurement system [1]. In particular, the stretch-wire method is well suited for measuring the harmonic contents of lattice magnets, such as dipole, quadrupole and sextupole magnets. Various stretch-wire fixtures were designed to meet the requirement of each measurement condition. The coil support structure is simpler than that of the traditional rotating or harmonic coil system [2]. In this paper, the system description, experimental results and performance of the stretched-wire system are presented. Meanwhile, the measurement algorithm and theory [3] of the first, second field integral and harmonic field components will be described.

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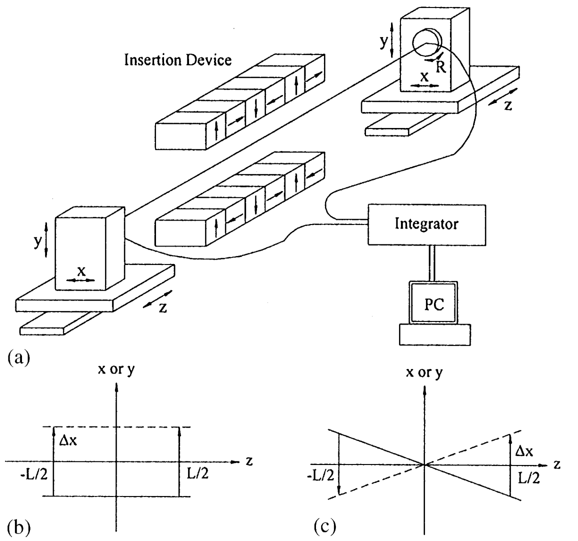

Fig. 1. (a) The system diagram of the open-loop wire for the first and second field integral measurements, (b) moving method for measuring the first field integral, and (c) moving method for measuring the second field integral.

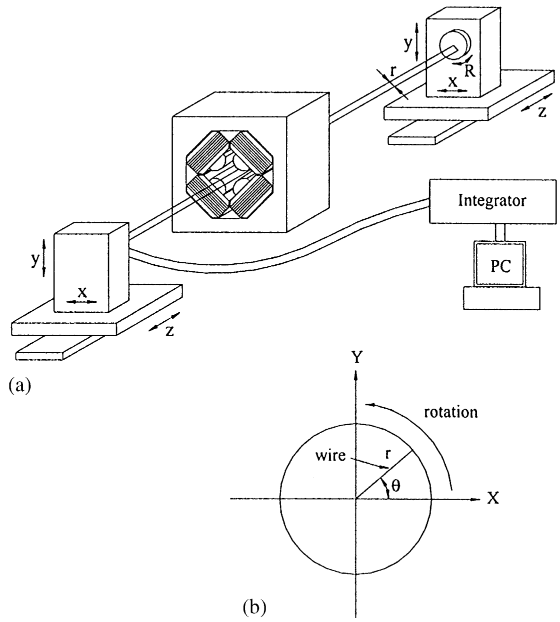

Fig. 2. (a) The system diagram of the closed-loop wire for the harmonic field integral measurement, and (b) moving method for measuring the harmonic field integral.

2. Stretch-wire measurement system

The system consists of two motorized X–Y–Z stages with rotors (see Figs. 1 and 2). The X and Y stages are for positioning and translating the stretch wire, respectively; while the Z stages are for stretching the wire to reduce sag. The rotators rotate a coil. Wire fixture is applied for centering and fixing either the open-loop (Fig. 1) or the closed-loop (Fig. 2) coil. In this wire fixture, the wire of the coil is on the rotation axis. The PC performs as the main control unit. Two stepping motor control cards (PC-STEP-4A-CL), Digital I/O board (NI-PC-DIO-24), and NI-AT-GPIB card, were installed to execute remote control and data acquisition [4]. There is an extra coil length at the coil terminal to leave out the electrical contact which is between the rotating coil and the stationary electronic devices. LabVIEW application program was developed on the main control unit with Microsoft windows 3.1-98 [5]. The data acquisition is carried out in an external trigger mode from the optical scalar signal to reduce the position error.

3. Measurement theory and analysis

There are three measurement schemes in this work. One is for measuring the first field integral of the insertion device to determine the electron beam angle deviation. The second is for measuring the second field integral of the insertion devices to determine the electron trajectory. The third scheme measures the harmonic field components of lattice magnets to find the multipole field components. The first two methods use the open-loop wire system (Fig. 1), while the third one uses the closed-loop wire system (Fig. 2).

3.1. First field integral measurement

A wire consisting of N-turn stretched multi-strand coils is to pick up the voltage signal $V = -N\,\mathrm{d}\Phi/\mathrm{d}t$ induced from the magnetic flux variation $\Delta\Phi = \int\int B\,\mathrm{d}x\,\mathrm{d}z$ by moving the wire in the transverse plane. The wire is inserted into the magnetic field region and the wire terminal is directly connected to the integrator. The first field integral, $I_x = \int B_x\,\mathrm{d}z$ and $I_y = \int B_y\,\mathrm{d}z$, are obtained from the induced voltage integrated in time while the wire is displaced as indicated in Fig. 1.

$$I_y = \frac{\int V\,dt}{N\Delta x}, \quad I_x = \frac{\int V\,dt}{N\Delta y}, \tag{1}$$

where, Δx and Δy are the displacements between two consecutive measurements on the transverse axis (Fig. 1(b)). Eq. (1) can be converted to the total angle deviation of the electron beam by $-\gamma mc/e$. The optimized value of the displacements is $\Delta x = 4$ mm for obtaining the high precision and special resolution with coil moving speed of 3 mm/s.

3.2. Second field integral measurement

The second field integral measurement is similar to the first field integral measurement except that the moving direction of the X stages or Y stages at different side is opposite to each other as shown in Fig. 1(c). Therefore, the displacements Δx and Δy of the wire depend on the longitudinal position. Consequently, the second field integral, $II_x = \int\int B_x(z')\,dz\,dz'$ and $II_y = \int\int B_y(z')\,dz\,dz'$, can be expressed [3] as Eq. (2).

$$II_y = -\frac{L}{2}\left[\frac{\int V\,dt}{N\Delta x} + I_y\right], \quad II_x = -\frac{L}{2}\left[\frac{\int V\,dt}{N\Delta y} + I_x\right], \tag{2}$$

where L is the length of magnet. Therefore, Eq. (2) can be converted to the total position variation of the electron by -$\gamma mc/e$.

3.3. Harmonic field components measurement

If the wire fixture on the rotator is changed to the closed-loop configuration with a radius r which will fit the bore radius of the multipole magnet, one side of the wire will lie on the rotating axis of the two rotors, i.e., $r = 0$, and the other side will lie on the radius $r = R$, as seen in Fig. 2(a). When the coil rotates as in Fig. 2(b), the induced voltage can be expressed as

$$\int_{t(\theta_i)}^{t(\theta_{i+1})} V\,dt = N\int_{-L/2}^{L/2} dz \int_{\theta_i}^{\theta_{i+1}} B_r R\,d\theta, \tag{3}$$

where θ_i is the angle at the ith position of the wire. The harmonic fields components of A_n and B_n can be obtained by a Fourier transform of the sampling data of $\int V\,dt$.

$$\sum_{n=1}^{\infty} a_n\cos(n\theta) + b_n\sin(n\theta) = \sum_{n=1}^{\infty} \frac{2R^nN}{n}[A_n\cos(n\theta) + B_n\sin(n\theta)]\sin\left(\frac{n\Delta\theta}{2}\right), \tag{4}$$

where $\Delta\theta = 360°/2^7$ is the angle between two consecutive sampling data. For easy characterization of magnet quality, the normalized integral harmonic components of skew term $A_{n,j}^{\text{skew}}$ and normal term $B_{n,j}^{\text{nor}}$ of the lattice magnet are derived as

$$A_{n,j}^{\text{skew}} = \frac{r_{\text{ref}}^{n-j}A_n}{B_{\text{ref},j}}, \quad B_{n,j}^{\text{nor}} = \frac{r_{\text{ref}}^{n-j}B_n}{B_{\text{ref},j}}, \tag{5}$$

where n and j is the harmonic term and magnet type, respectively (i.e., $j = 1,2,\ldots$ is the dipole, quadrupole magnet and so on), and $B_{\text{ref},j}(r_{\text{ref}})$ are the fundamental components (the radius of good field region) of each kind of magnet.

4. System precision and discussion

This system was used to measure the insertion device (lattice) magnets and evaluate the system precision with wire length of 2 (0.5) m. These magnets include a 1 m long elliptical polarized undulator with 5.6 cm period and 2.6 cm magnet gap and the lattice magnets, a 10 cm long dipole corrector with 10 cm magnet gap, a 20 cm long quadrupole magnet with 3 cm bore radius, and a 14 cm long sextupole magnet with 4 cm bore radius. In our system, the number of turns of the wire is $N = 10$. The EPU5.6 was measured back and forth three times within five minutes and averaged to get high precision of the field integral in the range of $x = \pm 20$ mm. Fig. 3 shows the first and second field integral along the transverse x-axis between $x = \pm 20$ m. The whole system precision of the first (second) field integral is about 1.5 G cm (70 G cm^2). The electron angle (position) deviation derived from the first (second) field integral between $x = \pm 10$ mm is within

Table 1
The measurement results of normalized harmonic field strength and the precision of dipole corrector, quadrupole, and sextupole magnet

n	Dipole (%)	Quadrupole (%)	Sextupole (%)
1	100 ± 0.01	0.20 ± 0.02	1.27 ± 0.03
2	0.34 ± 0.01	100 ± 0.01	1.05 ± 0.04
3	0.52 ± 0.01	0.03 ± 0.01	100 ± 0.01
4	0.16 ± 0.02	0.04 ± 0.01	0.11 ± 0.01
5	0.24 ± 0.01	0.01 ± 0.01	0.10 ± 0.01
6	0.10 ± 0.01	0.56 ± 0.01	0.03 ± 0.01
9	0.06 ± 0.01	0.05 ± 0.01	0.12 ± 0.02
10	0.04 ± 0.01	0.23 ± 0.01	0.06 ± 0.01
14	0.04 ± 0.01	0.01 ± 0.01	0.05 ± 0.01
15	0.05 ± 0.01	0.01 ± 0.01	0.06 ± 0.02

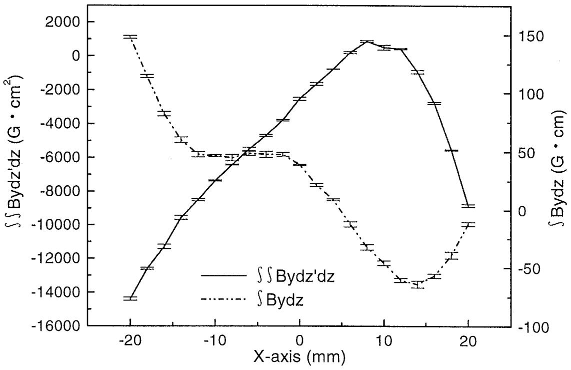

Fig. 3. Distribution of the first and second field integral measurements as well as its error bar on different transverse x-axis positions.

± 0.01 mrad ($\pm 10\,\mu$m) in our 1.5 GeV storage ring.

The dipole corrector, quadrupole, and sextupole magnets were excited by 10, 50, 50 A and the fundamental field integrals 0.041 T/m, 2.81 T, and 82 T/m were obtained by the sampling rate of 5 ms. The normalized expansion coefficients and the precision are listed in Table 1. The harmonic field strength and precision of each harmonic component shown in the table are obtained from the normalization of Eq. (5). This table indicated that the precision of the each harmonic component is within 0.01% except certain harmonic term in the sextupole magnet.

Several crucial issues have been solved to get the system precision: (1) the electronic drift of the integrator (Metrolab PDI 5025) [4,5] has been compensated by the data analysis, (2) the precise optical linear and rotor encoders are used for positioning the wire to the accurate position and angle, and (3) the signal noise is reduced by the low-pass filter. However, some issues still need to be solved in order to enhance the system precision and accuracy: (1) deviation reduction of the wire rotating axis by precise mechanical machining and the exact assembly between the coupler and rotor, (2) the improvement of gain linearity and stability versus temperature and time of the integrator, and (3) the sag [4] of coil. We should optimize the precision for the longer magnets by the Be–Cu wire, although it will pick up higher noise signal compared with Cu wire alone. Finally, to maintain the accuracy of each harmonic component within 0.01%, the $\pm 0.05\%$ uncertainty of the systematic errors should be calibrated and adjusted by reversing the polarity of the excitation current and changing the direction of magnet.

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