MAGNETIC FIELD MEASUREMENT SYSTEM FOR PLS-II MAGNETS*

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Abstract

The Pohang Accelerator Laboratory (PAL) has been carrying out upgrade project on the Pohang Light Source (PLS) to PLS-II. The overall lattice of the storage ring for PLS-II has been changed, thus many magnets installed in storage ring at present should be replaced with new or modified ones. The magnetic field qualities of the quadrupole and sextupole magnets will be measured using new rotating coils which were fabricated using an aluminum-oxide bar for the first time at PAL. The data acquisition system for field measurement has been rebuilt to make it simple and to have a good signal to noise ratio. In this presentation, the design parameters of the rotating coil and some test results are presented.

INTRODUCTION

The Pohang Accelerator Laboratory (PAL) has been carrying out performance upgrade of the Pohang Light Source (PLS); (1) beam energy increased from 2.5 to 3.0 GeV, (2) beam current increased from 200 to 400 mA, (3) beam emittance reduced from 18.9 to 5.9 nm-rad, and (4) number of spaces for insertion devices increased from 10 to 20. The storage ring lattice of the upgraded PLS (PLS-II) is different from PLS to secure more straight sections. All quadrupole and sextupole magnets need to be measured to confirm their qualities. The number of quadrupole and sextupole magnets for PLS-II is 96 and 144, respectively.

The rotating coil method (RCM) has been used widely to measure conventional DC magnets for particle accelerators [1]. RCM has an advantage over the Hall probe method; a reproducible real time measurement of integrated field properties, multipole coefficients, and magnetic axis of magnet is possible [2-3]. Field measurement systems using RCM had been developed about eighteen years ago at the beginning of the PLS project. The previous rotating coils were made using epoxy fiber glass (EFG) as a winding form. However, EFG has the following undesirable properties; (1) the its glass granules made machining difficult, (2) it can be deformed easily by the high temperature generated during machining, (3) its surface after machining rough, and (4) it tends to deform in time because of poor stability against temperature and humidity. Thus all previous rotating coils can not be reused for PLS-II.

Four rotating coils have been fabricated for the PLS-II magnets using aluminum-oxide, Al_2O_3, in 2009. Aluminum-oxide has excellent properties; (1) its melting temperature is very high and it can maintain mechanical strength up to 90% at > 1100^{o}C, (2) thus it does not deform during machining process, (3) it has excellent dielectric properties from DC to high frequency, (4) it has high mechanical strength and stiffness, and (5) it has good property against humidity.

When using a complex number notation, the rotating coil measurement generates the magnetic vector and scalar potentials and the high-order magnetic multipoles [4]. Results of rotating coil measurement can thus be directly incorporated with the calculation of beam dynamics. This paper configures as follows. First, the theoretical background and complex notations of fields for the rotating coil measurement are described. Next, the measurement system is described. Finally, measured results performed on a quadrupole magnet are presented.

ROTATING COIL DESIGN

A typical geometry of a rotating coil, which has been designed for the multipole field measurement of a magnet, is shown in Fig. 1. The outer coil package has M turns and the inner coil has $\mu \times M$ turns The parameters for β_1, β_2, r_1, and r_2 are described in the Fig. 1.

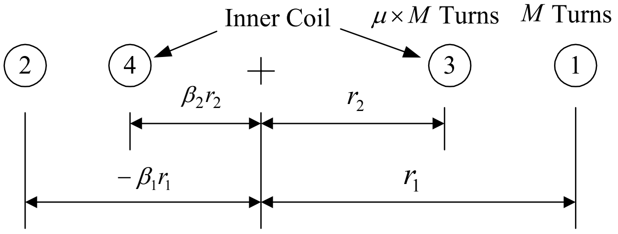

Figure 1: Typical geometry of a rotating coil for multipole field measurement.

The magnetic flux linking each coil package is given in Eq. (1). When the inner and outer coils are connected in series such that one coil has opposite polarity of induced voltage to the other coil (bucked mode), the contributions of the nth multipole component to Ψ_n is given as

$$\Psi_n = l_{eff} M \,\mathrm{Re}\left(C_n e^{in\theta} r_1^n \sigma_n\right) \tag{1}$$

where $\sigma_n = 1 - (-\beta_1)^n - \mu\rho^2\left(1 - \left(-\beta_2\right)^n\right)$ is the coil sensitivity for measuring the nth multipole components, l_{eff} is the effective length of coil and $\rho = r_2 / r_1$.

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The output of a voltage integrator at time t is $\gamma[\Psi_n(t)-\Psi_n(t_0)]$, where γ is the integrator gain and t_0 is the time at which the integrator is turned on. When the rotating coil is rotated around an axis, the flux is measured as a function of angular position, $\Psi = \Psi(\theta)$. Since $\Psi(\theta)$ is a periodic function in θ and can be represented as a Fourier series

$$\Psi(\theta) = \sum_{n=0}^{\infty}(\alpha_n \cos n\theta + \beta_n \sin n\theta) \qquad (2)$$

The multiple coefficients a_n and b_n can be obtained from Eq.1 and Eq. 2 as follows :

$$a_n = \frac{n\alpha_n}{\gamma M l_{eff}\sigma_n r_1}\left(\frac{r_0}{r_1}\right)^{n-1}, \quad b_n = \frac{n\beta_n}{\gamma M l_{eff}\sigma_n r_1}\left(\frac{r_0}{r_1}\right)^{n-1}$$

where r_1 is the maximum coil radius and r_0 is the normalized radius.

MEASUREMENT SYSTEM

A block diagram of the field measurement system is shown in Fig. 2. The measurement system consists of a stepping motor assembly, an analog signal processor, a digital voltmeter (DVM), and a computer. The stepping motor assembly is composed of the S83-62 stepping motor, SX-6 motor driver, and E83 incremental encoder from Compumotor Co. The stepping motor rotates at 25,000 steps per revolution and the encoder generates 1000 pulses per revolution. The encoder output pulses are used to trigger the analog-to-digital converter (ADC). The stepping motor driver is controlled by the computer through RS232C interface. The control and calculation procedures are programmed in the computer using the 'C' language.

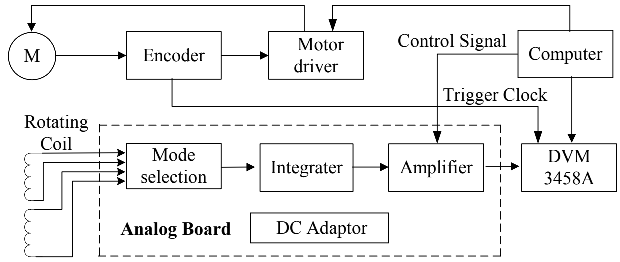

Figure 2: Block diagram of the field measurement system using the rotating coil.

For quadrupole magnet measurement, any misalignment between the magnetic axis and the coil rotation center appears as a dipole component. So, sensitivities of coil for both dipole and quadrupole components should be small for multipole error measurement. A quadrupole rotating coil has been designed to have the following parameters: $\beta_1 = 0.75$, $\beta_2 = 0.65$, $\mu = 1.5$, and $\rho = r_2 / r_1 = 0.7$. These parameters result in a bucked mode sensitivity of 0.0175 for dipole component and 0.01303 for quadrupole component, which are low enough for multipole error measurement of quadrupole magnets. The relative multipole sensitivities of the coil calculated are given in the Fig. 3.

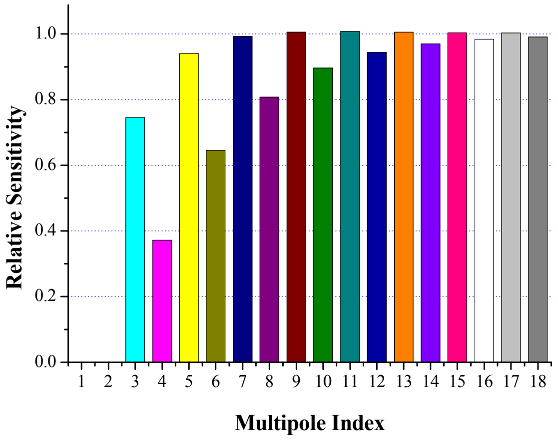

Figure 3: The sensitivity of the quadrupole rotating coil. where $\beta_1 = 0.75$, $\beta_2 = 0.65$, $\mu = 1.5$, and $\rho = 0.7$.

Cross-sectional view of the quadrupole rotating coil assembly is given in Fig. 4. The rotating coil has two coils: the outer ② and inner ③ coils. The inner coil was wound on the inner coil slot formed on the cylindrical aluminum-oxide core ①. Two aluminum-oxide spacers were installed on the coil slot after winding the inner coil. The outer coil was wound on the outer coil slot which had been formed on the aluminum-oxide spacer. The coil keeper maintains position of the outer coil. Both inner and outer coils were made using a 20-bundle multifilar wire from the MWS Wire Industries. After winding the multifilar wires on the coil slots, the wires were connected in series on a small PCB ④ inside the rotating coil holder. Number of turns was 400 for the outer coil and 600 for the inner coil. The aluminum-oxide core was mounted to the coil housing using two ring bearings. A stepping motor ⑤ from Paker Co. was mounted on the coil housing. The stepping motor has an incremental encoder ⑥ which is used to monitor the angular position of the coil. The axis of stepping motor was connected to the axis of rotating coil using a mechanical coupler. The stepping motor makes three turns for field measurement: one for acceleration, another for measurement, and the other for deceleration. The induced coil voltage was sampled only on the second turn where the motor speed is constant.

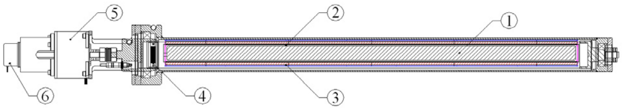

Figure 4: A cross-sectional view of the quadrupole rotating coil assembly. ① : Aluminum-oxide frame; ②: Outer coil; ③: Inner coil; ④: PCB for wire serialization; ⑤: Stepping motor; ⑥:Incremental encoder.

The induced voltage of the rotating coil is pre-processed using analog circuits before analog-to-digital conversion. The analog pre-processing circuits include buck/unbuck mode selection switches, attenuators, an analog integrator, and a reset circuit for the analog integrator.

The Agilent 3458A digital voltmeter is used as the ADC for field measurement. It has a resolution of 100nV at 10 V input range, which is good enough for PLS-II field measurement. The integrator output voltage is converted into digital data by ADC whenever the clock generated by the incremental encoder triggers the ADC. The stepping motor makes three revolutions per measurement and the encoder generates 1000 pulses per revolution. So, each measurement generates 3,000 digital data. Among them, only 1000 digital data which are obtained at the second revolution, where the angular speed is uniform, are used for further analysis. The measured 3,000 digital data are transferred to the computer via GPIB. The 8-bit digital output of the USB-6501 board from National Instruments controls the function of analog circuits, such as integrator in/reset and amplifier gain, etc.

To reduce system noise, all digital signals are isolated by photo couplers and all electronic equipments are designed to share a common ground. It was found that the noise from the stepping motor driver is the dominant source of noise. So, to reduce this noise, AC lines and grounds for the stepping motor drive circuits are separated from those for the analog circuits for signal processing. The integration error caused by a small offset voltage of operational amplifier is corrected for each measurement using the data analysis software.

EXPERIMENTAL RESULTS

The Fig. 5 shows both induced signals of bucked and unbuckled where attenuation factor and gain of amplifier were applied different values on the two modes.

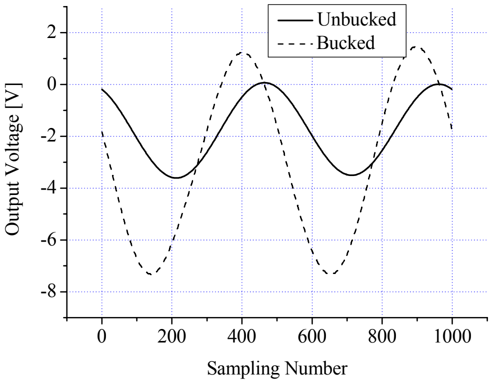

Figure 5: Sampled induced voltage of two modes, buck and unbuckled with different gain and attenuation ratio.

The rotating coil was mounted to the magnet easily by jigs which are designed for only measurement. After demagnetization process, magnetic field properties were measured. The fundamental component was measured using the only outer coil first. Next multipole components using the outer and inner coil together, what we called it bucked mode, were analyzed by the Fourier series expansion as Fig. 6.

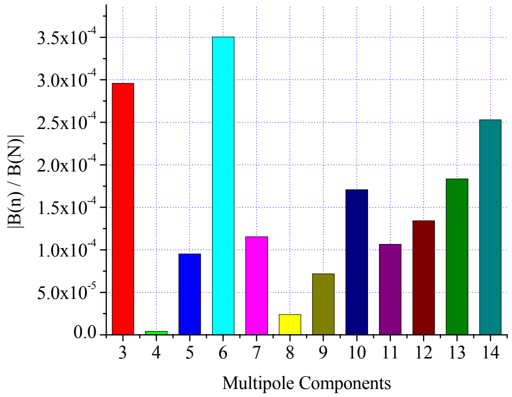

Figure 6: Measurement results: normalized multipole components to the quadrupole component were shown.

CONCLUSIONS

Two different types of rotating coils for the quadrupole and sextupole magnets of the PLS-II were assembled using the aluminum-oxide for the first time at PAL which has much better properties comparing to the old one, epoxy fiber glass for the PLS, against the deformation nature effected by humidity and time flowing.

The analog signal processing board was simplified removing complicated functions. The attenuation circuits including rotating coils were modeled and calculated the attenuation factors to apply them to integrator gain.

The fundamental and multipole components of the quadrupole and sextupole magnets were successfully measured using the new rotating coils and signal processing board. These field measurement systems will be adapted to measure the PLS-II magnets in 2010.

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