MULTIPOLE MAGNETIC MEASUREMENTS USING A LOCK-IN AMPLIFIER TECHNIQUE*

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Abstract

Magnetic measurement systems for accelerator magnets typically use relatively complicated rigid rotating coils and digital integrators to capture the integrated coil signal as a function of angular position of the coil. This technique has proven to be reliable and accurate for measuring the field quality of conventional multipole magnets; however, the design and construction of the rotating coils ultimately determine the accuracy of the measurement system. A different concept and implementation of a simple stretched-wire rotating coil will be described. This system utilizes a single-turn radial coil continuously rotating at a fixed angular velocity. The coil signal and a reference pulse are sampled with a 24-bit ADC. A lock-in technique or an FFT can be used to determine the harmonic content of the signal and thus calculate the main field strength and angle, multipole coefficients, and magnetic center offsets. The main advantages of such a system are ease of coil manufacturing and simple mechanical system design.

INTRODUCTION

Motivation for this project was prompted by the need to quickly measure modified multipole magnets for the APS storage ring. Existing six-pole horizontal/vertical dipole corrector magnets were modified to become horizontal correctors and skew quadrupoles. A need to measure the multipole components and magnetic center of these new combination magnets prompted the design of a new, relatively simple multipole magnet measurement system.

The previous APS multipole magnetic measurement system used G-10 and ceramic Morgan coils that were supported in air bearings and driven by a DC motor. A 16-bit absolute encoder was used to trigger an integrator based on rotary position. This system had not been used in many years and the quality of the coil assemblies was questionable. We had recently completed magnetic measurements of a superconducting undulator (SCU) and had used a single-turn stretched coil to measure the integrated dipole components. Since we already had much of the hardware required, we decided to use a single-turn radial coil for harmonic field measurements of multipole magnets.

SYSTEM OVERVIEW

The following is a list of some of the features of the new multipole measurement system:

- Continuous coil rotation without slip rings
- Quasi-real-time measurements of individual multi-pole components using a lock-in amplifier (LIA)
- Measurement of the integrated magnetic field strength, multipole coefficients, magnetic-center offsets, and magnetic angle
- Automatic alignment of quadrupole and sextupole magnet positions relative to the center of rotation of the coil

The key components for the multipole measurement system were two Newport RGV100BL precision rotary stages. The precise control of position, velocity, and simultaneous timing allowed synchronous operation of both stages as if the coil wires were rigidly linked.

The system utilized a single-turn stretched coil in a radial configuration, as shown in Fig. 1. The coil-wire was 100-µm-diameter CuBe. The coil-wire ends were held in place with plastic fixtures connected to the rotary stages, as shown in Fig. 2. Coil fixtures can easily be made overnight on a 3D printer, so changing the radius of the coil would be a simple matter of changing the fixture radius. The coil was tensioned by moving the signal-end rotary stage in the longitudinal direction until the sag was minimized. The coil-wire sag was typically less than 200 µm when using a 1.5-m-long coil. Optical alignment telescopes were used to confirm the coil dimensions and alignment to approximately 50-µm accuracy.

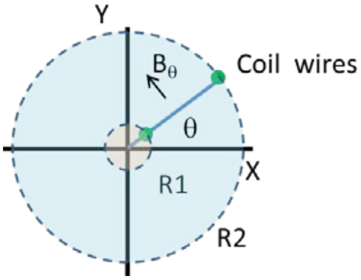

Figure 1: Radial coil configuration is sensitive to the radial component of the B field.

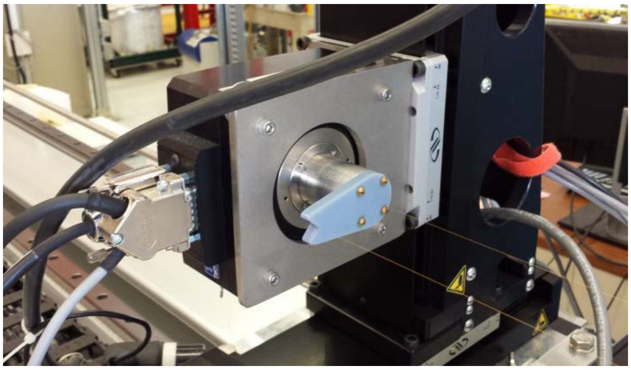

Figure 2: Signal-end rotary stage looking at the plastic coil positioning fixture.

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The non-signal-end rotary stage was located at a fixed position; the signal-end rotary stage could be moved in all axes for alignment purposes. The signal-end rotary stage contained a sealed mercury-filled rotary connector from Mercotac. The rotary connector provided a means of coupling a low-noise signal from the rotating coil to the fixed signal cable. This rotary stage also utilized an opto-interrupter, which provided a trigger pulse for angular reference of the coil signal, as shown in Fig. 3.

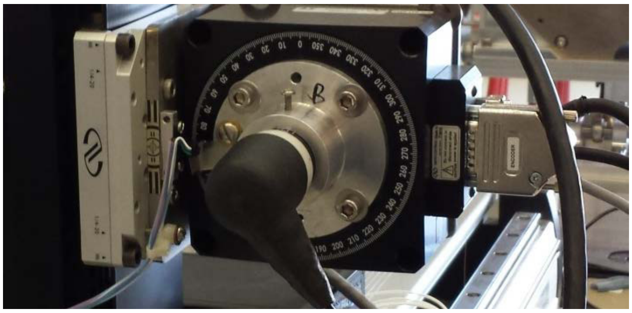

Figure 3: Signal-end rotary stage looking at the rotatable connector and opto-interrupter (left of stage scale), which provided a pulse for phase reference.

The two rotary stages were aligned to be co-linear, level, and parallel, and rotate in unison with a constant velocity of 1 rps. The coil signal could be amplified with gains of 10, 100, or 1000 before being digitized by a National Instruments dynamic signal analyzer (DSA) module.

LOCK-IN-AMPLIFIER

The integrated harmonic field components could each be separately measured using the rotating coil and a lock-in amplifier. Using National Instruments hardware and a LabVIEW software module downloaded from National Instruments, the LIA was easily implemented at very little cost. The software required two input signals, a reference and a measured signal, which were measured with the 24-bit analog-to-digital inputs of a PXI-4462 DSA module. The sampling rate of the DSA was 200 kHz and 25600 samples were recorded per coil revolution. This gave an angular resolution of 0.25 mRad between samples. The reference signal was provided by the opto-interrupter pulse, which occurred once per revolution.

The reference and measured signals were processed with LabVIEW software and the integrated field components were derived. The vertical and horizontal components were derived simultaneously and the individual harmonic number to be measured could be chosen through a user selectable software option. The software used the measured frequency and phase of the reference signal to create a new sine wave reference that was mixed with the measured signal [1]. The result of mixing the two signals was a DC signal and an AC signal with twice the reference frequency. The DC level was proportional to the measured signal at the reference frequency and was used to calculate the magnitude of the integrated field components. The LIA software also returned the phase of the measured signal relative to the reference signal.

The LIA measurement technique was convenient for initial magnet alignment or studying the effects of magnet coil current changes. The results can be observed in quasi-real time after a short settling time. The disadvantage of the LIA was that an individual measurement for each desired harmonic was required to fully characterize a particular magnet.

MULTIPOLE MEASUREMENTS

A multipole measurement (MM) technique was developed whereby ten rotations of the coil voltage signal were digitized and time averaged to create an averaged single-rotation time record. The time record harmonic content was then processed by a built-in LabVIEW FFT routine. The magnet main field strength, angle, and all harmonics were then calculated. Total time per measurement was approximately 15 seconds.

The rotating coil voltage waveforms of three different magnetic fields are shown in Fig. 4. The dipole and skew quad waveforms were generated by a six-pole combination dipole and skew quadrupole magnet. The SR quad waveform was from an APS 0.5-m storage ring quadrupole. The dipole and skew quadrupole signals had visibly large harmonic content. The skew octupole (a_4) is especially large at -344.3×10^{-4}. The relative normal and skew harmonic coefficients for each magnetic field from Fig. 4 are listed in Table 1. The b_2 and a_2 components represent the normal and skew quadrupole components, respectively. The components are relative to the main field for each case, and all are calculated at a specification radius of 10 mm.

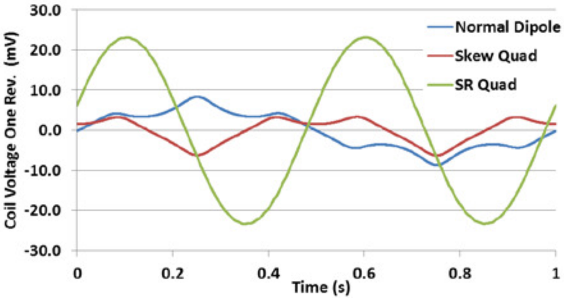

Figure 4: Digitized coil voltage waveforms for three different magnetic fields. “Normal Dipole” and “Skew Quad” are two configurations of the same six-pole magnet structure. The “SR Quad” is a 0.5-m-long APS storage ring quadrupole magnet.

Table 1: Relative Multipole Coefficients (10^{-4} units) at 10-mm Specification Radius (b_2, a_2 are quadrupole)

Harmonics	Normal Dipole	Skew Quadrupole	Normal Quadrupole
b_2, a_2	-7.4, -2.1	0, 10000	10000, 0
b_3, a3	2.8, 0.2	-16.9, 11.0	-1.0, -0.5
b_4, a_4	-0.5, -0.5	1.2, -344.3	-0.2, 0.1
b_5, a_5	-0.1, 0.3	-.1, 0.3	-0.004, 0.0

Ambient Field and Magnet Alignment

The typical measurement sequence for a quadrupole magnet began with recording the ambient field with the magnet under test fully degaussed. The dipole components, due to the Earth's field, were then subtracted from subsequent measurement of the dipole components. This was most important for accurate measurement of the magnetic offset and alignment of quadrupole magnets since a quadrupole magnet is aligned to minimize the integrated dipole field. After the ambient measurement, the magnetic offsets and angle were measured and the magnet was aligned with a motorized magnet support table. Multipole measurements were then performed at the prescribed coil currents.

Measurement Repeatability and Resolution

A series of 16 measurements were performed over the course of 10 minutes using a storage ring 0.5-m quadrupole magnet. The results of the repeatability of the magnetic offsets and magnet angle are shown in Fig. 5. The coil radius for these measurements was 38.14 mm.

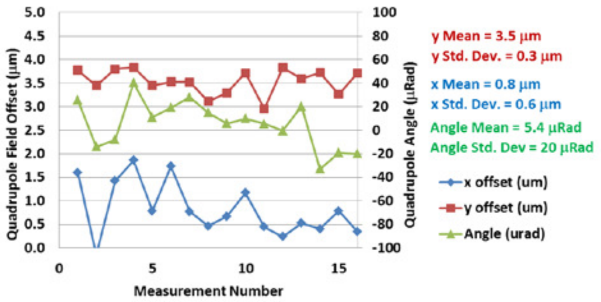

Figure 5: Plots of the measured magnetic offsets in x and y from the coil rotation center and the magnetic angle relative to gravity. The standard deviation of the offsets and angle were less than 1 µm and 25 µRad, respectively.

HARMONIC CALCULATIONS

The theory of harmonic magnetic measurements has been well known for many years [1], but can be confusing due to differences in notation and conventions. Two invaluable references used by the authors were by A. Jain [2] and L. Walckiers [3].

The instantaneous single-turn coil voltage can be described by:

$$\mathrm{V(t)} = \sum_{\mathrm{n=1}}^{\infty} \mathrm{K}_n \left[C_n e^{-in(\omega t+\delta)} \right], \qquad (1)$$

where

$$\mathrm{K_n} = \mathrm{L}\omega \left[\frac{\mathrm{R_2^n - R_1^n}}{\mathrm{R_{spec}^{n-1}}} \right]. \qquad (2)$$

The complex Fourier components are

$$\mathbf{V_n} = \mathrm{K_n}\mathbf{C_n} = \mathrm{K_n}(\mathrm{B_n} + i\mathrm{A_n}), \qquad (3)$$

where L is the magnet length; R_2 and R_1 are the coil major and minor radii, respectively; δ is the reference phase angle; R_{spec} is the specification radius; and B_n and A_n are the normal and skew integrated multipole coefficients, respectively. The relative multipole coefficients listed in Table 1—b_n and a_n—are B_n and A_n normalized to the main field components.

CONCLUSION

The implementation of a single-turn CuBe radial coil has proven to be an effective means to measure the harmonic content of accelerator magnets. By combining very accurately controlled rotary stages, a rotatable signal coupler, and a 24-bit DSA module, measurements of the main and harmonic field errors were possible with a simple radial coil design. Continuous measurements of an individual harmonic could be performed using the LIA technique, or when complete harmonic components were desired, the MM technique was chosen.

Repeatability, as shown in Fig. 5, was quite good. The absolute accuracy was dependent on how well the dimensions of the coil could be measured; typically it was on the order of 0.5% for a 38-mm coil radius. Presently the repeatability of the magnetic center measurements of the new system is approximately an order of magnitude better than the previous APS measurement system. Further testing of the system will be performed on calibration magnets and compared to previous APS multipole measurements performed over 20 years ago.

ACKNOWLEDGMENTS

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