A NEW HELMHOLTZ COIL PERMANENT MAGNET MEASUREMENT SYSTEM*

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Abstract

A Helmholtz coil magnet measurement system was upgraded at the Advanced Phone Source (APS) to characterize the insertion device permanent magnets [1]. The system uses the latest state-of-the-art field programmable gate array (FPGA) technology to compensate the speed variations of the magnet motion. Initial results demonstrate that the system achieves a measurement precision better than 2×10^{-4}.

INTRODUCTION

Most insertion devices (IDs) at the APS are permanent magnet based [2]. Before the magnets are installed onto the IDs, each of them has to be characterized and sorted to ensure that the magnets in a single ID are even and as identical as they can be to minimize the integral fields and the phase errors of the device.

The APS Helmholtz coil system, designed to characterize magnets used in the APS permanent magnet IDs, has been recently upgraded. The system has improved the measurement precision by an order of magnitude. The system now consists of a pair of identical coils, a horizontal rotary table with two full ceramic spherical bearings, and a digital encoder on its main rotating shaft driven by a servo motor.

The control and data acquisition system is a PXI-based computer system. With the latest state-of-the-art field programmable gate array (FPGA) technology, the system is capable of synchronized measurements of position (0.05 degree in resolution), time (25 ns), and voltage (16 bit).

THEORY OF OPERATION

A Helmholtz coil consists of two identical circular coils placed coaxially and separated by a distance equal to the radius of the coils. When the two coils carry the same current in the same direction, it creates a near uniform magnetic field within the center region between the two coils. Therefore, a magnet placed within the center region can be treated as a magnetic dipole by a Helmholtz coil system.

Moving a magnet inside the coils causes the magnetic flux change that in turn generates a voltage signal in the coil:

$$V = -d\Phi/dt\,, \qquad (1)$$

where V is the voltage, Φ is the magnetic flux, and t is time.

By rotating the magnet inside the Helmholtz coils, measuring the voltage signal in the coils, and integrating the signal over time, we have [1]

$$\Phi = -\int_{t_0}^{t_1} V(\theta.t)dt$$

$$= -\frac{1}{k} * (M_V * \sin\theta + M_H * \cos\theta) + C, \qquad (2)$$

where V is the voltage signal, θ is the rotation angle, k is the Helmholtz coil constant, M_V and M_H are the vertical and horizontal components of the magnetic moment, respectively, and C is the offset constant.

$$k = \left(\frac{5}{4}\right)^{\frac{3}{2}} \frac{R}{\mu_0 N}\,, \qquad (3)$$

where R is the coil radius, μ_0 is the free space permeability constant, and N is the number of turns in each coil.

Fitting the integral with a sinusoidal function of

$$A * \sin\theta + B * \cos\theta + C \qquad (4)$$

we have the vertical component of the magnetic moment:

$$M_V = kA \qquad (5)$$

and the horizontal component of the magnetic moment:

$$M_H = kB. \qquad (6)$$

Usually magnet vendors provide the components of the intrinsic induction information.

$$B = \mu_0 m = \frac{\mu_0 M}{V}, \qquad (7)$$

where m is the magnetization vector and V is the volume of the magnet. Hence the components of the intrinsic induction are

$$B_{V,H} = \mu_0 m_{V,H} = \frac{\mu_0 M_{V,H}}{V}. \qquad (8)$$

SYSTEM DESCRIPTION

The Helmholtz coil magnet measurement system consists of the subsystems shown in Figure 1.

A set of Helmholtz coils that consists of a pair of identical coils are made of copper material and the support structure is of G-10. The mean diameter of the coils is 26 inches. The coils are mounted coaxially, separated by a distance of 13 inches. Each coil has 392 turns.

A horizontal rotary stage holds the magnet in the center region of the coils. The aluminum stage shaft is supported by two full ceramic spherical bearings. A magnet mounting stage is supported at the end of the aluminum shaft. The mounting stage is centered between the two coils. The stage is motorized, driven by a servo motor that coupled to the other end of the stage via a 10:1 rotary inline gearbox. A hollow-shaft rotary encoder is

* Work at Argonne was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No DE-AC02-06CH11357.

Figure 1: Helmholtz coil magnet measurement system.

mounted inline on the stage shaft. The encoder has 360 degrees freedom with 0.05-degree resolution. The rotary encoder is used to accurately define the angular position of the magnet mounted on the rotary stage.

The FPGA reconfigurable data acquisition card has eight 16-bit-resolution analog inputs, 96 digital inputs/outputs, 25-ns time resolution, and 80-kB on-board memory. The digital I/Os are programmed to read the encoder positions. The analog inputs are configured to measure the coil signals synchronized with the position readouts and the time durations in real time.

A PXI shelf with a control card hosts the FPGA card and the software program.

SYSTEM CONTROL SOFTWARE

LabVIEW-based system software has been developed to coordinate the stage control and data acquisition. Figure 2 shows the schematic layout of the system control and data acquisition architecture. The system can be accessed via the Internet from anywhere anytime, wired or wireless, through the embedded http interfaces inside LabVIEW.

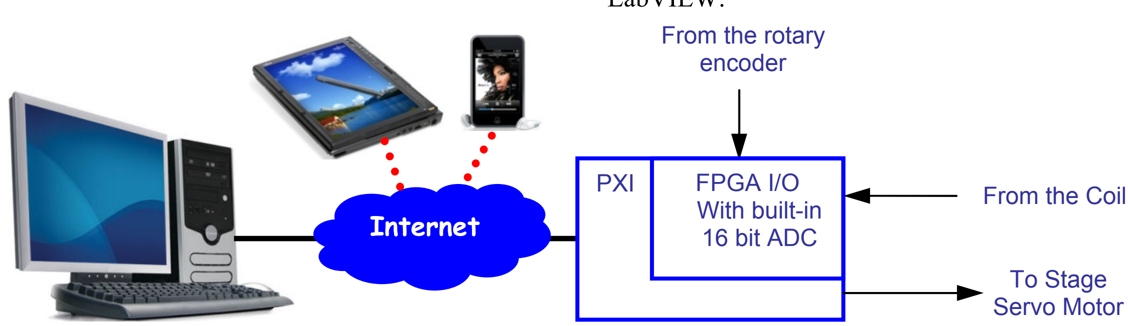

Figure 2: System control and data acquisition architecture schematic layout.

The system software has a main control and data acquisition interface and modules. The main control and data acquisition interface rotates the magnet stage and sets the FPGA hardware to wait for the magnet angular position to go to the start position. When the angular position hits the start position mark, the hardware will simultaneously write the following data to its memory on the fly:

1. The angular positions of the magnet with an angular resolution that can be set down to 0.1 degree per step.
2. The integrated Helmholtz coil voltage signals across each angular step with a rate of 4.3 µs per sample at 16-bit resolution.
3. The number of samples integrated within each angular step.
4. The time duration within each angular step.

When the magnet angular position reaches the 360 degree mark, the hardware sends an interrupt to the module. It integrates the signal, fits the integrated data with a sinusoidal function to extract the field integral components, and plots the raw data along with the fittings.

The measurement analysis and plot module reads the saved data file, analyzes the data, and plots the raw data along with the fittings and analysis results.

The advanced motion control module fine tunes the stage position and encoder readout. It has one submodule: the motor velocity and acceleration control and monitoring. The submodule sets and monitors the velocity and acceleration parameters of the servomotor.

The system parameter database module consists of three copies in a single file: the current, the backup and the default. The default copy is read-only. Each copy contains, among others, the motor velocity, acceleration and system calibration constants, encoder reference indexes, encoder resolutions, stage-gear ratio, motor-velocity ratio, motor-acceleration ratio, and motor resolutions. The system parameter database control module and its advanced system parameter database control module manipulate and manage the system parameter database.

The integral measurement FPGA firmware module resides on the FPGA reconfigurable card. It monitors the encoder position, the coil voltage, and time. It also interfaces with the measurement modules and submodules. The FPGA module executes all the tasks in parallel at the speed of 40 MHz.

The main control and data acquisition interface, each module, and submodule has its own GUI interface except for the FPGA firmware module. The main interface provides access to all the modules and the submodules. It checks the status of the FPGA reconfiguration data acquisition. If the FPGA card is not initialized or is running on different firmware, the module will download and initialize the card with the appropriate firmware. It also checks the status of the servomotor. If the motor is not initialized, it will try to reinitialize it.

SYSTEM CALIBRATION

The system calibration is the measurement of the Helmholtz coil constant k as defined in equation (3). Based on the design of R = 13 inches and N = 392, the k value shall be 0.09362 Ampere per Gauss. However, the real system k value has to be calibrated.

Hardware required for the calibration is a calibrated current power supply and a calibrated magnetometer. The DC current power supply used for calibration was a Kaithley 6221 DC current source. The magnetometer was a Bartington Instruments Mag-03 Magnetic Field Sensor. The calibration results are shown in table 1.

Table 1: Calibration Results

Field (G)	+100 mA	-100 mA
Mean value	1.081190	-1.081188
Standard deviation	0.000058	0.000032

Therefore, the k constant is 0.09249 Ampere per Gauss, which is very close to the design value of 0.09362 Ampere per Gauss.

MEASUREMENT RESULTS AND DISCUSSION

A typical magnet measurement taken with the Helmholtz coil measurement system is shown in Figure 3.

The file header field shows the basic parameters of the measurement. The rotary stage scanning speed was 2 revolutions per second. Each measurement consists of scans along the +y axis (+Mx/+Mz), +x axis (+My/+Mz), -y axis (-Mx/+Mz), and –x axis (-My/+Mz). Averaging over the components cancels the mechanical asymmetries of the system. The integral plot field shows a specific integrated raw scan along with its sinusoidal fitting. Next to the integrals field are the fitting parameters to that specific measurement. According to equations (5) and (6), the sine component represents the vertical component of the field integral while the cosine component represents the horizontal component. Below the integral field plot display are the magnetic moment components $m_{(ave)}$, the measurement errors $\sigma_{(err)}$, the moment density components $\rho_{(density)}$, the magnetic moment orientations $\theta_{(angle)}$, as well as the total moment M, and its orientation to the z axis θ_z.

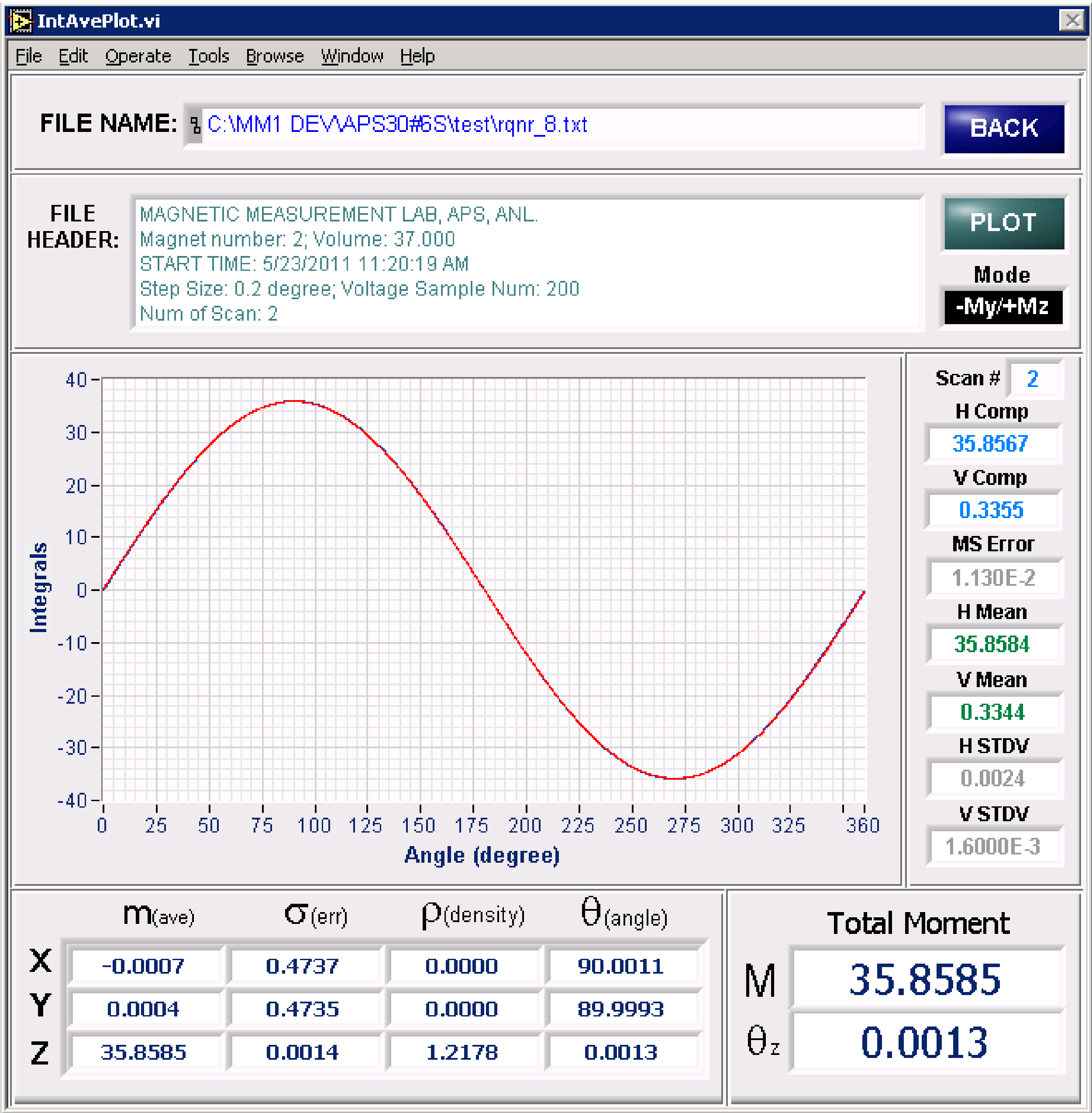

Figure 3: Magnet measurements.

CONCLUSION

A new Helmholtz coil magnet measurement system has been constructed, tested, and commissioned at the Advanced Photon Source. With the latest state-of-the-art FPGA technology, the system achieves measurement precision of 2×10^{-4}.

REFERENCES

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