STRETCHED WIRE FLIP COIL SYSTEM FOR MAGNETIC FIELD MEASUREMENTS*

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Abstract

A flip-coil system using a stretched wire measuring the magnetic field properties is described. This system is similar to the conventional rotating coil system except that the stretched wires are used to measure the magnetic field properties. This system has advantage of simple fabrication and flexible operation so that different length and different bore magnets can be easily measured using the same system. The system has two loop coils to buck the dominant fundamental field so as to increase the measurement accuracy. The stretched wire loop coil system is tested to verify its performances and the results are discussed. The analyzing methods and various efforts for keeping the system in high accuracy are presented. Measurement results with this loop coil system are compared with the previous results.

1 INTRODUCTION

Usually the magnetic field distribution in accelerator magnets are two dimensional meaning that the length of the magnet is longer compared to the magnetic gap or bore radius. Also the effects of the magnetic fields on the charged particles are determined by the integrated effects of the magnets. Taking into account the general characteristics of accelerator magnets, the magnetic measurements of the accelerator magnets are usually carried out using rotating coils that uses the Faraday induction law[1]. The rotating coil system has advantages in the fast measurement speed, and built in characteristics of higher order multipole decomposition. Also it can be easily extended to measure the difference of a magnet from a reference one using a null measurement. But the rotating coil system is difficult to fabricate precisely. For example, machining non-conducting (ceramic or fiber-glass) raw material is non trivial. Also the rotating coil measurement is limited to the specific target magnet and one need new rotating coils even for slightly different magnets. In this paper, a flipping coil system that was used to measure residual field integrals[2][3] are extended by adding angular resolution and bucking mechanism for higher sensitivity for the higher harmonic fields. The efforts for the angularly resolved flipping coil system are described.

2 FLIPPING COILS

For two dimension magnetic field configuration, it is well known that the complex potential given by

$$F(z) = A(x,y) + iV(x,y) = \sum_{n=1}^{\infty} C_n \left(\frac{z}{r_0}\right)^n = \sum_{n=1}^{\infty} C_n \, (r/r_o)^n \, e^{in\vartheta}$$

is analytic, where $\vec{B}(x,y) = \nabla \times (A(x,y)\vec{z})$, or $\vec{B}(x,y) = -\nabla V(x,y)$ [4]. Here, r_0 is a normalizing radius to make all C_n has same dimensionality of Tesla-m. Usually r_0 is taken as a "good field radius" and it's set to 30mm for PLS quadrupole measurements. It can be easily shown that the vector potential $A(x,y)$ and the scalar potential $V(x,y)$ satisfy the Cauchy-Riemann conditions satisfying the analyticity requirements of the complex potential $F(z)$. The magnetic flux linking a coil loop can be easily calculated as $\Phi(\theta) = \int \vec{B} \cdot d\vec{a} = L_{eff} \; A(\vartheta)$.

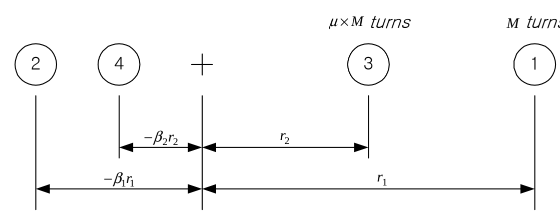

Figure 1: Coil geometry.

Therefore, measuring magnetic flux linking the loop coil, one can easily calculate the multipole contents of the magnets using above equations. The coil geometries used for the experiments are shown in Figure 1. In Fig. 1, outer coil has M turns that enter the plane of the paper at $x = r_1$ and exit at $x = -\beta\, r_1$. The inner coil has a reversed directionality to the outer coil and has $\mu \times M$ turns. For this coil geometry, the output voltage from the integrator is related to the flux as follows

$$\Phi(\theta) = GV_o(\theta) = -L_{eff} \sum_{n=1} M \left(\frac{r_1}{r_o}\right)^n \sigma_n \left(a_n \cos n\theta - b_n \sin n\theta\right)$$

Here, G is the integrator gain, a_n and b_n are defined through $C_n = a_n + ib_n$. σ_n is the sensitivity coefficients and determined from the coil geometry as follows:

$$\sigma_n = 1 - (-\beta_1)^n - \mu \left(\frac{r_2}{r_1}\right)^n (1 - (-\beta_2)^n)$$

From these equations, the integrated multipole contents of a magnet can be easily recovered. For our cases, the geometrical parameters are: r_1 = 24mm, r_2 = 12mm,

β_1 = 0.5, β_2 = 0.5, M = 10, and μ =4. With these parameters, when inner and outer coils are connected in series, the quadrupole component has zero sensitivity and only higher order multipole components are visible. For fundamental measurement, only outer coils are used for better signal to noise ratio.

The block diagram of the flip coil system is shown in Fig. 2. This system consists of flip coils, two xyz stages, driving motors, analogue integrator, a DVM, PC and so on. A multifilament wire from the MWS Wire Industries was mounted on fixtures of two XYZ stages. Two flipping motors were rotated by the common pulse source which comes from the OEM010 indexer from Parker Co. In this way, the two motors can rotate synchronously. The induced voltage at the coil is integrated by the analogue integrator after selecting the bucked or unbuckled mode. For bucked mode, the two coils connected in series to cancel out the fundamental component so as to increase the sensitivity of the higher multipoles. The self-resistance of the outer coil is 308 Ω in 10 turns and inner coil has 1208 Ω in 40 turns.

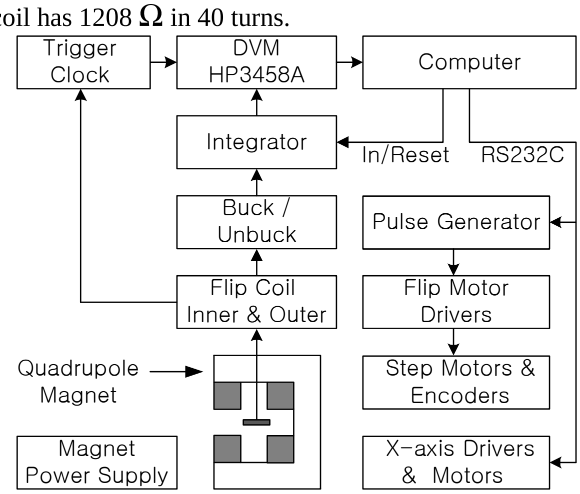

Figure 2: Block diagram of the flip coil system

The integrated voltage was digitized by a DVM HP3458A while flip-coil was revolved with constant velocity. The DVM was triggered by the clocks of the incremental encoder for sampling the data. The encoder value is directly proportional to the angular positions of the flip coil. The sampling rate is 2000 samples/revolution with 4-byte integer per sample, and the sampled data were transferred to the PC in burst mode by the GPIB. A typical sampled voltage waveform was shown in Fig. 3.

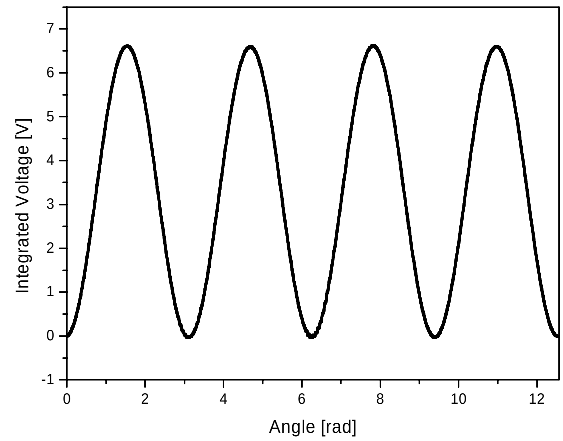

Figure 3: Integrated voltage waveform of the quadrupole magnet.

Two different AC voltages for 120V and 220V are applied to the system to increase signal to noise ratio in the system. One 120V is for signal processing part, and the other 220V for stepping motor drives which are the major noise sources because it is switching about 140V DC to make stepping pulses. The ground of the integrator, encoder clock counter and stepping pulse generator were isolated each other by using a photo-coupler and transformer. The reproducibility of this system was measured by testing PLS Q3 magnet for I=87A. Twenty successive measurements showed that integrated quadrupole strength is $B' r_0 L_{eff} = 1.11022\times10^{-1} \pm 1.20\times10^{-5}$ Tm. Therefore, the relative accuracy is about 1.08×10^{-4} which is close to the requirement of 1.00×10^{-4}.

3 MEASUREMENTS AND ANALYSIS

The measured fundamental components by this system are compared with those results of the previous rotating coil system. We found out the differences of two results was less 1.7% which might be came from mechanical tolerance of coil fixtures. The analyzed multipole components, which were normalized by the fundamental components of $B_2 r_0 L_{eff}$, were shown in Fig. 4. With more careful aligning and calibration, we believe the agreement can be improved to better than 0.1%.

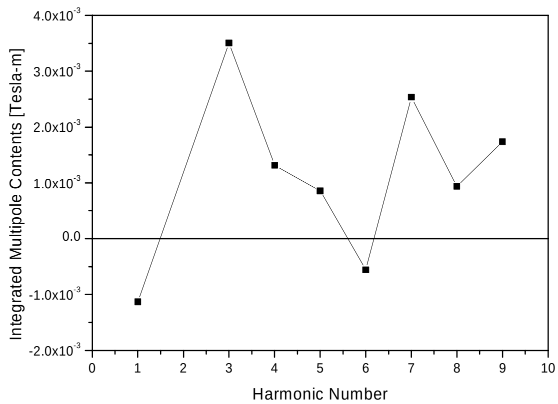

Figure 4: Multipole components normalized by the fundamental components.

To test the sensitivities of the measurement system with displacement, the rotating axis was artificially moved for horizontal and vertical direction from -100 μm to 100 μm. The measured magnetic axis changes are compared with the displacements. For displacement Δ, the changes in the multipole contents can be estimated from the following equation using the binominal theorem.

$$B_x - iB_y = i\frac{dF(z)}{dz} = \sum_{n=1}^{\infty}\frac{inC_n}{r_0}\left(\frac{z+\Delta}{r_0}\right)^{n-1} = \sum_{n=1}^{\infty} d_n\left(\frac{z+\Delta}{r_0}\right)^{n-1}$$

$$= \sum_{n=1}^{\infty} D_n\left(\frac{z}{r_0}\right)^{n-1}$$

$$D_n = \sum_{k=0}^{\infty}\binom{n+k-1}{n-1} d_{n+k}\left(\frac{\Delta}{r_0}\right)^k$$

Here, d_n are the multipole coefficients before the displacements and D_n are the coefficients after the displacements. From above equations, it can be seen than all harmonics which have smaller harmonic number than the fundamental components are affected by the displacement which agrees with intuition. Harmonics which are higher than the fundamental components change very little. The differences are on the order of $O(\Delta / r_0)$ which is negligible in most cases. In Fig. 5 the measured magnetic axis are shown when the rotating axis is moved from -100 μm to 100 μm in X-direction. The linearity is excellent. The y-direction movement also shows similar linear behaviour in the vertical direction..

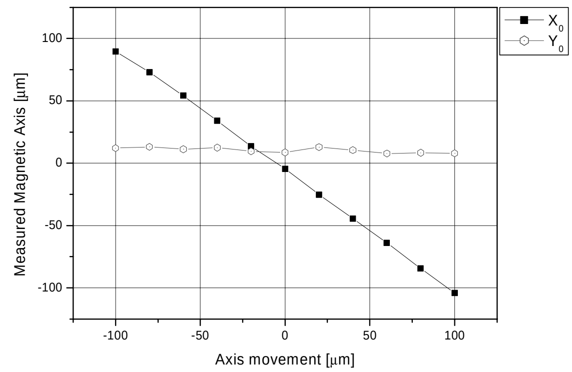

Figure 5: The measured magnetic axis change versus the artificial mechanical movement. X-axis is moved from -100 μm to 100 μm without vertical movements. Filled rectangle represents the measured X-axis while the open circle shows the measured vertical axis position.

5 SUMMARY AND DISCUSSION

In this paper, development of angularly resolved flipping coil system is described. This system has advantage in the flexibility that can measure wide variety of core radius and length of the magnets using the same system. The measurement results are compared with the old results from the previous rotating coil system. The difference was less than 1.7% which may be attributed to the geometrical inaccuracies of the flipping coil system. The relative reproducibility is about 1.08×10^{-4} which are good enough for the fundamental measurements. More exact calibration procedures are needed with methods than can align the coil with respect to the magnet efficiently and accurately. More detailed studies will be carried out in the future to make it a useful tool for versatile magnetic measurement system.

6 REFERENCES

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