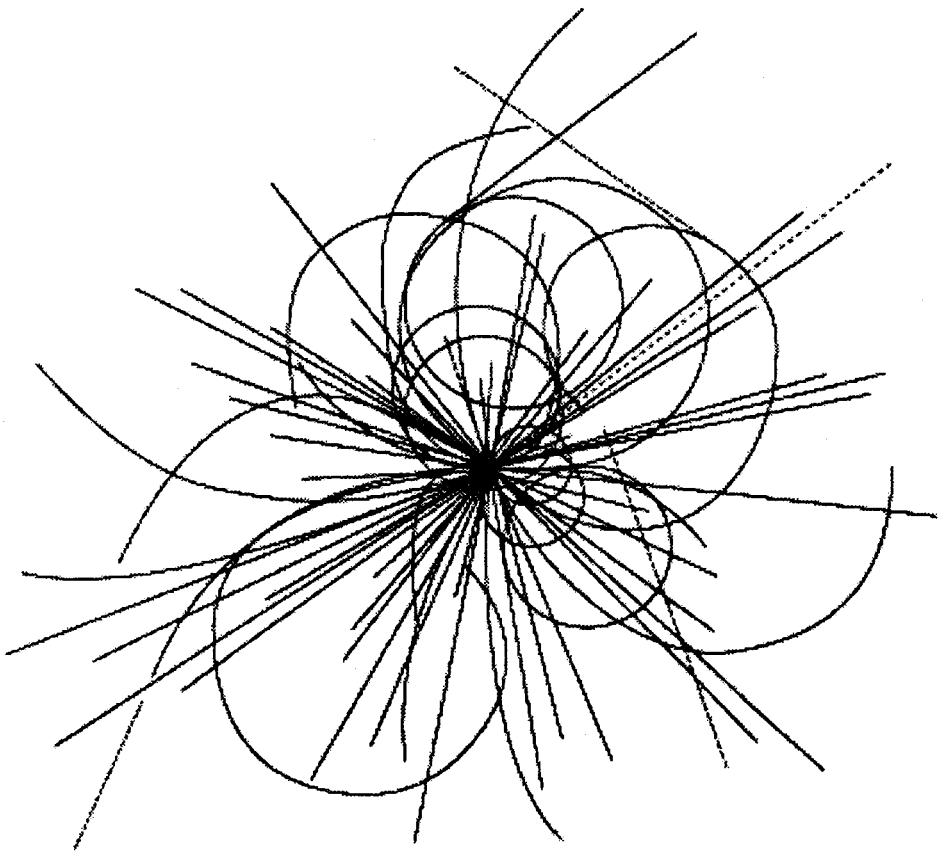
SSCL-Preprint-289

SSCL-Preprint-289
April 1993
Distribution Category: 400

W. Li
M. Coles

Systematic Error Analysis of Rotating Coil Using Computer Simulation



Superconducting Super Collider Laboratory

To be published in *Supercollider 5*

SSCL-Preprint-289

Systematic Error Analysis of Rotating Coil Using Computer Simulation*

Wei-chuan Li and Mark Coles

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

April 1993

*Presented at the Fifth Annual International Symposium on the Super Collider, May 6–8, 1993 San Francisco, CA.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

SYSTEMATIC ERROR ANALYSIS OF ROTATING COIL USING COMPUTER SIMULATION

Wei-chuan Li and Mark Coles

SSC Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237-3946

INTRODUCTION

This report describes a study of the systematic and random measurement uncertainties of magnetic multipoles which are due to construction errors, rotational speed variation, and electronic noise in a digitally bucked tangential coil assembly with dipole bucking windings. The sensitivities of the systematic multipole uncertainty to construction errors are estimated analytically and using a computer simulation program.

SIMULATION PROGRAM

The simulation program reproduces the operation of the magnetic field quality measurement apparatus or "mole"[1] by generating a sequence of voltage samples and a sequence of intersample times. This data is then input to the standard mole data analysis program and the resulting estimates of magnetic multipole field content are compared to the input field model. This is accomplished by integrating the $(\vec{V} \times \vec{B}) \bullet d\vec{L}$ component of voltage (where $\vec{V}$ is the velocity of the element $d\vec{L}$ of the wire filament and $\vec{B}$ is the local magnetic field) along all of the coil filaments of each coil. The voltage series generated are then analyzed using the standard analysis program in order to compute the harmonic content of the measured magnetic field. Arbitrary magnetic field configurations can be input and the construction details of the mole can be varied in order to estimate the sensitivity of the calculated multipole outputs to these changes. F-mole configuration[2] parameters are used in the simulation program.

*Operated by the Universities Research Association, Inc., for the U. S. Department of Energy under Contract number DE-AC35-89ER40486.

It was determined that most of the error sensitivity is proportional to the amplitude of the input field harmonics, so a "worst case" field was used for this study which was obtained by using the upper limit of the systematic multipole specification plus three times the standard deviation specification.[3] For this study, various construction parameters, such as coil bowing, misalignment, etc., were varied independently. Sensitivities were estimated by first simulating the ideal F mole design and then comparing the results of that simulation to the results obtained using non-ideal construction parameters. The input magnetic field is shown in Table 1.

Table 1. Comparison of the input and output multipole coefficients.

Multipole index	Input skew a (units)	Input normal b (units)	Output skew a (units) ideal case	Output normal b (units) ideal case	Output skew a (units) nominal case	Output normal b (units) nominal case
1	3.79	1.54	3.79	1.54	3.804	1.545
2	1.082	5.45	1.082	5.45	1.089	5.484
3	0.986	0.506	0.986	0.506	0.9958	0.511
4	0.17	0.74	0.1699	0.7401	0.1723	0.7496
5	0.166	0.076	0.166	0.07599	0.1685	0.07716
6	0.043	0.08	0.04299	0.08	0.04379	0.08144
7	0.04	0.04	0.04001	0.04	0.04077	0.04076
8	0.0305	0.0425	0.0305	0.0425	0.0311	0.04335

In order to check the correctness of the simulation and analysis program the nominal geometry of the coil was simulated. Also, the individual filamentary wires of the cable were modelled as infinitely thin wires and all wires within a bundle were placed at the same angle and radial position on the coil. Table 1 shows the normal and skew harmonics input to the simulation and the computed results obtained after simulation and analysis using this idealized geometry. They are in good agreement. This simulation program was also run using the nominal coil geometry but with a 0.006 inch space between conductors within a wire bundle. These results are shown in Table 1 as "nominal harmonics". Note that the nominal harmonics contain some small errors due to the finite angle subtended by the wire bundles of each coil. Hereafter, unless specified, all the harmonics will be compared to these nominal harmonics.

A typical configuration of dipole bucking coils has one tangential coil and two bucking coils. The amplitude of the dipole field in a typical SSC magnet is approximately ten thousand times greater than the amplitude of the next larger harmonic coefficient. The influence of the dipole term is removed using a technique called "bucking". Digital bucking, the technique considered in this simulation, was developed by the BNL magnetic measurement group.[4] The induced voltage on the tangential coil at time t can be expressed as

$$V_T(t) = -2B_0 N_T r_T L_T \omega \sum_{k=1} (r_T)^{k-1} \sin\left(k\frac{\Delta}{2}\right) \times \{ b_{k-1} \cos[k(\omega t - \beta)] + a_{k-1} \sin[k(\omega t - \beta)] \} \quad \text{(EQ 1)}$$

where B_0 is the fundamental dipole field strength, N_T is the number of turns of the tangential coil, r_T is the radius, L_T is the length, ω is the average rotating speed, Δ is the opening angle, β is the initial offset angle, and a_k and b_k are the kth skew and normal multipole, respectively. The induced voltages on the two bucking coils, V_1 and V_2, are given by similar expressions. From these three voltages we can compute a_k and b_k.

As an example of the sensitivity to a coil construction error, consider what happens when the radius of the dipole bucking coil is changed to $r+dr$ from r. The measured values of the a_k and b_k harmonics will be changed by the amounts

$$da_k = \frac{\partial a_k}{\partial r}dr + \frac{\partial a_k}{\partial \Delta}\frac{\partial \Delta}{\partial r}dr \qquad \text{and} \qquad db_k = \frac{\partial b_k}{\partial r}dr + \frac{\partial b_k}{\partial \Delta}\frac{\partial \Delta}{\partial r}dr. \qquad \text{(EQ 2)}$$

The second term in each sum is necessary because the tangential opening angle Δ is computed from the measured ratio of the tangential and dipole bucking coil signals. This effect was also simulated using the computer simulation program, setting dr to 5, 10 and 20 mils. The largest changes occurred for the sextupole components; da_2/a_2=-0.082 and db_2/b_2=-0.069 when dr=20 mils. We estimated these changes analytically using the first order approximation (EQ 2), which resulted in da_2/a_2=-0.069 and db_2/b_2=-0.069 for dr=20 mils. The two methods are consistent. Since the errors scale approximately linearly with dr, we can extrapolate that $|dr|$ should be less than 0.53 mils to keep $|db_2| \leq 0.01$ units.

This kind of first order estimation can be used for other construction error analyses. We verified that all the analytical estimations are consistent with our simulation program. (For a detailed discussion of error analysis and simulation, see the references 4 and 5.)

Table 2. The tolerance requirements for the mole needed in order to have systematic error of less than 0.01 units with a "worst case" magnetic field.

Parameter	Nominal value	Tolerance
bow	0.0	1.6 mils or 0.041 mm
sag	0.0	40 mils or 0.1 mm
twist	0.0	40 mrad
bearing misalignment	0.0	0.24 mils or 0.0061 mm
radial error of tangential winding	12.3063 mm	0.24 mils or 0.061 mm
radial error of bucking winding	12.3063 mm	0.53 mils or 0.041 mm
angular error of tangential winding	0.262 mm	130 mrad
angular error of bucking winding	3.141 rad	7.1 mrad
parallelism error of tangential winding	0.0	0.48 mils or 0.012 mm
parallelism error of bucking winding	0.0	2.0 mils or 0.052 mm
angular velocity of coil	2.0943	0.021 rad/s
random electrical noise	0.0	2.8 nv(rms)

MECHANICAL TOLERANCE OF THE COIL CONSTRUCTION

We have studied various sensitivities of a rotating coil to construction errors, rotational speed variation and electronic noise. The construction errors include: (1) the radial position of the coil winding may be offset parallel to the rotating axis; (2) the coil winding may have a cone shape; (3) the coil may be bowed during the manufacturing process; and (4) the bearing of the coil may be offset from the geometrical center of the coil. The harmonics are quite sensitive to these errors. Other errors, such as the tangential coil angle offset and the coil twist are less problematic and can be easily compensated if digital bucking is used as a measurement technique. Sagging can be removed provided that a reliable centering correction method is used. If the required maximum tolerable uncertainty on any harmonic coefficient is less than 0.01 units, the coil must satisfy all the tolerance requirements summarized in Table 2. While demanding, these requirements are not impossible to satisfy if careful consideration is given to the fabrication methods to be employed. It was also found that the ideal centering correction not only corrects the center offset, but also fully corrects the sag effect and partially corrects the bearing center offset.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Kiseon Kim and Yu Ping Zhao for many useful discussions regarding magnetic measurements and Fourier spectral analysis.

REFERENCES

1. P. Wanderer, "Production Techniques For Measuring SSC Accelerator Magnets," ICFA Workshop on Superconducting Magnets and Cryogenics, BNL, May 1986.
2. One of a series of moles designed by Brookhaven National Lab. Engineering Drawing Number 25-1105-02.
3. "SSCL Site Specific Conceptual Design," SSCL-SR-1056, July 1990.
4. G. Ganetis, J. Herrera, R. Hogue, J. Skaritka, P.Wanderer, and E.Willen, "Field Measuring Probe for SSC Magnets," Particle Accelerator Conference, March 19, 1987.
5. W.C. Li and Mark Coles, "Rotating Coil Simulation Study," MD-TA-201, May 1992.