

CALIBRATION OF ROTATING COIL ARRAYS FOR PARTICLE ACCELERATOR MAGNET TESTING

P. Arpaia¹, L. Fiscarelli^{1,2}, L. Walckiers²

¹ University of Sannio, Benevento, Italy

² European Organization for Nuclear Research (CERN), Geneva, Switzerland

Abstract: Synchrotron particle accelerators are mainly composed of magnets. Long dipole magnets are employed to bend and to contain the beam within a circular trajectory. Their field quality is usually tested by arrays of rotating coils. Typically the measurements must be affected by low uncertainty ($\pm 10^{-4}$) and the calibration of the sensing coils, in terms of surface and angle, is critical. In this paper, a new method for the coil calibration is presented. The method is firstly stated formally and then validated in an actual use case. Experimental results demonstrate the capability of the method to meet also constraining requirements.

Keywords: sensor calibration, magnetic measurements, accelerator magnets.

1. INTRODUCTION

In synchrotron particle accelerators, the beam is confined in a small region of space and forced to follow a definite circular path [1]. The most practical way to operate on accelerated charged particles is a magnetic field. In fact, electromagnets can be built with high mechanical and magnetic accuracy in order to produce in their aperture the required field distribution. Clearly, high-quality magnetic measurements are crucial during all the phases of design, construction, testing, and operation of accelerator magnets.

In magnet testing, quasi-static inhomogeneous magnetic fields are often measured by means of rotating coil fluxmeters [2]. A coil consists of several rectangular loops of conducting wire, usually stretched on a rigid core during the winding and then glued to assure a well-defined and stable geometry. By rotating in the magnetic field, the coil generates a voltage according to the Faraday's law. This signal is integrated in the time domain in order to obtain the magnetic flux. By knowing the coil geometry, the magnetic field can be obtained easily from the flux.

The length of main dipole magnets of a synchrotron is in a range from 2 m to more than 10 m. For practical reasons, the aperture as a whole of such magnets is tested by using an assembly of coils, organized as an array of segments, mechanically connected in order to turn rigidly [2].

The coil surfaces have to be calibrated magnetically by turning them individually in a reference dipole magnet [3]. Usually, the stability of the reference is verified by means of

a Nuclear Magnetic Resonance (NMR) teslameter, the most accurate device for measuring the magnetic field [4].

The angles between the segments forming the coil array have to be determined magnetically also. Specific calibration benches have to be developed in order to host the whole coil array and to provide the reference magnetic field [3].

The complete calibration procedure results to be very expensive in terms of operation time and resources. The procedure complexity leads to carry out the calibration only after the production and assembly of the coil. Calibration checks during the operating life of the transducers are unusual, although very useful.

In this paper, a new calibration method, based on a reference given by the Single Stretched Wire (SSW) measurement system [5], for rotating coil array is presented. In particular, in Section II the *proposal* is explained, and in Section III the *experimental results* are presented.

2. PROPOSAL

A rotating coil array for magnetic measurements on accelerator magnets mainly shows two kinds of nonideality [2]:

1. Actual and ideal surfaces of the sensing coil differ owing to manufacturing nonideality or to assemblage deformations (Fig. 1a).

2. The coils should be aligned along their longitudinal axes. During the assemblage, the angles are controlled by means of mechanical systems, not capable of assuring negligible errors (Fig. 1b).

The proposed method, to be carried out on the magnet under test directly, namely *in situ*, is based on:

1. a reference measurement of the integral magnetic field of the magnet by means of the SSW [5];

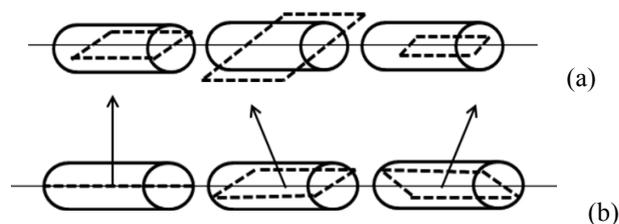


Figure 1. Coil surface (a) and angle errors.

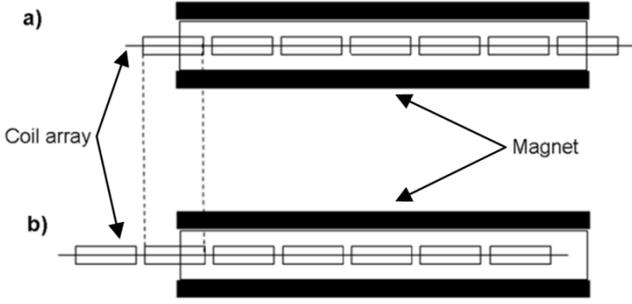


Figure 2. Coil array in the standard measurement position (a) and in the calibration position (b).

2. a set of measurements with the coil array in the standard measurement position (Fig. 2a) on the same magnet and the same conditions as the previous step;
3. and a further set of measurements with the coil array in the same conditions, but after a magnet displacement by exactly the length of one coil (Fig. 2b).

A rotating coil in a magnetic field produces an induced voltage. The integral of this voltage signal:

$$(1) \quad \Phi_i^a(\theta) = \varphi_i^a \cos(\theta + \alpha_i^a + \beta_i)$$

gives the magnetic flux ($\Phi_i^a(\theta)$) across the i^{th} coil at the standard measurement position a , as a function of the coil angular position θ with respect to the gravity (where φ_i^a is the flux amplitude, α_i^a the phase of the field with respect to the gravity measured by the coil, and β_i the coil angle).

The SSW system is chosen as reference owing to its high accuracy in measuring the integral field in accelerator magnets [5].

The array of coils can also measure the integral field with sufficient accuracy if:

- it is longer than the magnetic length of the magnet,
- and the field in the magnet is sufficiently homogeneous longitudinally so that the field across the empty spaces between coils can be extrapolated from the coil measurements.

In this case, the integral field can be computed as the sum of two terms:

$$(2) \quad \sum_{i=1}^N \varphi_i^a k_i l_i + \sum_{k=1}^{N-1} \varphi_{k+1}^a k_{k+1} d_k$$

where:

- φ_i^a is the flux amplitude measured by the i^{th} coil in the standard measurement position;
- l_i the length of the i^{th} coil;
- d_k the distance between the k^{th} coil and the next one;
- k_i the unknown surface coefficient [$1/\text{m}^2$] of the i^{th} coil;
- N the total number of coils in the array.

The first term is the field measured by the coils multiplied by their length (integral field), and the second term represents the contribution of the empty spaces

between the coils, under the hypothesis of field homogeneity.

The second set of measurements, with the coil array displaced of exactly the length of one segment, is used to obtain further $N-1$ equations from the equalities of the field, considered stable, measured by two different coils at the same position in the magnet:

$$(3) \quad \varphi_i^a k_i - \varphi_{i-1}^b k_{i-1} = 0 \quad 2 \leq i \leq N$$

The $i-1^{\text{th}}$ coil at the calibration position (superscript b) is exactly at the same place of the i^{th} coil at the standard position (superscript a).

A non-homogeneous determined system of N linear equations, whose unknowns are the surfaces k_i of the coil array, can be obtained by combining (2) and (3) and by considering the integral field computed from the measurements of the coils as equal to the integral field measured by means of the SSW B_{SSW} :

$$(4) \quad \begin{cases} \sum_{i=1}^N \varphi_i^a k_i l_i + \sum_{k=1}^{N-1} \varphi_{k+1}^a k_{k+1} d_k = B_{SSW} \\ \varphi_i^b k_i - \varphi_{i-1}^a k_{i-1} = 0 \quad 2 \leq i \leq N \end{cases}$$

The system can be solved easily and the solution vector k_i represents the surface coefficient of the coils composing the array.

An analogous analysis can be carried out also for the determination of the angles between segments. In this case, instead of taking into account the flux amplitude, the phases of the magnetic field measured by the coils (Eq. 1) have to be considered. Because of the measuring shaft supporting the coil array is rotating, an external reference cannot be used as reference for the angles. For this reason, the first coil has been chosen as angle reference.

From the two set of measurements, $N-1$ equations can be obtained from the equalities of the field angles measured by two different coils in the same position.

$$(5) \quad \begin{cases} \beta_1 = 0 \\ (\alpha_i^b + \beta_i) - (\alpha_{i-1}^a + \beta_{i-1}) = 0 \quad 2 \leq i \leq N \end{cases}$$

The non-homogeneous determined system of N linear equations (Eq. 5) can be written. The unknowns are the angles β_i of the coil array referred to the first coil element.

3. EXPERIMENTAL RESULTS

The proposed method has been validated at CERN on a measurement coil shaft for testing main superconducting dipole of the Large Hadron Collider (LHC) [6].

A significant measurement effort is being devoted to the investigation of dynamic field errors of the main dipole magnets. Rapidly varying magnetic fields have been measured by a new measurement station with high-speed rotating coils units and fast digital integrators (FDI) [7].

The LHC main dipole-superconducting magnet is long 15 m [8]. The magnetic length of the magnet is 14.343 m. Its bending radius is 2812.36 m (warm conditions) corresponding to a sagitta of 9.143 mm. The magnet is a

two-in-one structure and the two LHC beams circulate in opposite directions in the two apertures. The nominal field produced by the magnet is 8.36 T at a current of 11850 A.

For the magnetic measurements, a rotating shaft, composed of 12 rotating ceramic segments (1150 mm of length) each holding three tangential, equal, and parallel pick-up coils (Fig. 3), is placed in the aperture of the magnet [9]. One coil is used to measure the dipole field component (the so-called “absolute” signal), while the connection in series opposition with a second coil provides cancellation of the dipole (“compensated” signal) and ensures higher noise rejection for the measurement of harmonic error components. In such a measurement setup, the calibration of the surface of the sensing coils is clearly a key point for accurate results.

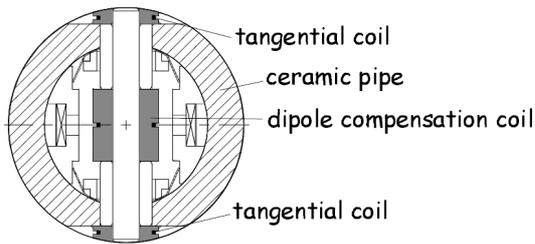


Figure 3. LHC rotating coil measurements shaft section.

The coil surfaces were calibrated in a reference dipole magnet before the assemblage on the shaft. In a second phase, the shaft was tested on the “shaft calibration bench”, in order to calibrate also the angles between segments.

The proposed method was selected to be used during a measurement campaign on a LHC dipole magnet as experimental validation (cryogenic tests are very expensive). A special bench was built in order to displace the shaft with an uncertainty of ± 1 mm (Fig. 4). A nominal current of 11850 A for the magnet was chosen in order to have a better SNR. The shaft was rotating at 60 rpm as trade off between high signal level and low mechanical vibrations [10]. The signals were acquired and integrated by means of a set of 12 FDI (one for each coil segment).

The two sets of measurements (standard position and calibration position) were carried out by rotating the shaft in both direction and averaging the results in order to cancel out the offset error.

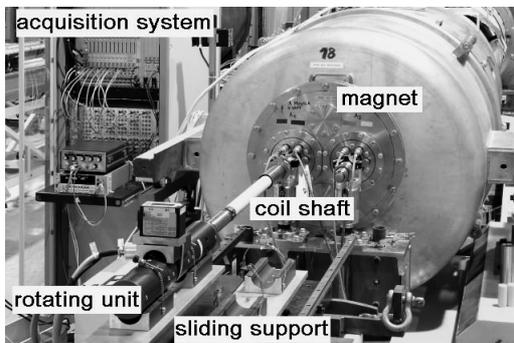


Figure 4. Measurement setup.

Then, the integral magnetic field strength of the magnet was measured by means of the SSW.

The data were analyzed according the proposed method (Section II). The surface coefficients were compared to the standard calibration performed on the reference dipole magnet. The differences are in the order of a few 10^{-4} units (Fig. 5).

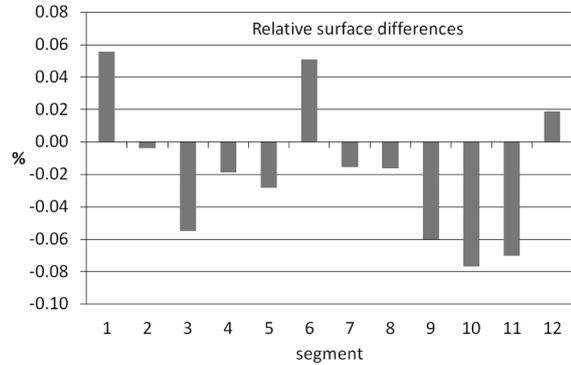


Figure 5. Surface coefficient differences between standard calibration and proposed method relative to the coefficient of each coil.

The deviation from the standard calibration values can be explained by considering basically three sources of errors:

1. The proposed method requires an accurate displacement of the shaft. In experimental conditions, the displacement is accurate in the order of 1 mm.
2. The coil segments are embedded on the shaft with an uncertainty in the order of ± 1 mm also.
3. The two sets of measurements are carried out in actual measurement conditions, whereas standard calibration is done in a controlled environment.

These errors could affect the coil surface estimation by producing relative deviations in the order of 10^{-4} .

The results for the coil angles were compared to the calibration carried out on the shaft calibration bench.

Differences in the order of 0.8 mrad were observed (Fig.6). Also a deterministic effect can be noticed. The differences increase along the shaft from the 7th to the 12th segment.

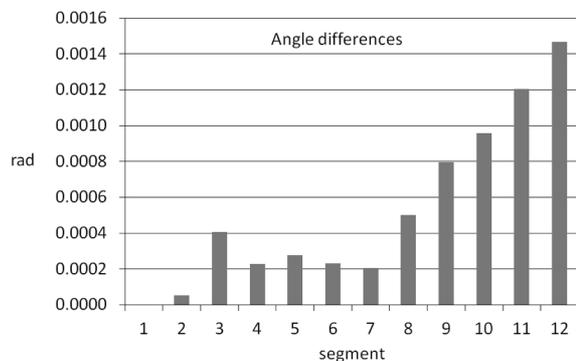


Figure 6. Angle differences between standard calibration and proposed method.

This effect could be explained by analyzing the working mechanism of the “shaft calibration bench”. It is based on a sliding reference magnet with a length of 1500 mm. The coil segment has to be centred in the magnet with high accuracy in order to have a null fringe field contribution. A typical displacement error, in the order of 1 mm, could produce a perceptible effect on the angle estimation (~1 mrad).

4. CONCLUSIONS

A new method for calibrating the surface coefficients and the relative angles of array of coils is presented.

An experimental case is reported in order to validate the method. The results demonstrate the capability of the procedure to reach the requirements imposed by the accelerator magnet testing (10^{-4}) both for the surface and angle calibrations.

The proposed calibration, as opposed to classical methods based on reference magnets, has the practical advantage of carrying out the test on the magnet under test and in standard measurement conditions with the twofold benefits of:

1. repeating the calibration during a measurement campaign by controlling the heat of the coil sensors with very low costs in terms of time and resources;
2. taking into account and compensating the environmental influence parameters.

The proposed procedure, presented as specific method for magnet testing, could be generalized to all the measurement situations where an array of sensors can be rigidly displaced.

REFERENCES

- [1] A. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering*, 2nd ed. (World Scientific Publishing, London, 1999).
- [2] L. Walckiers, “Magnetic measurement with coils and wires,” in CERN Accelerator School CAS 2009: Specialised Course on Magnets, Bruges, 16–25 June 2009 (CERN, Bruges, 2009), pp. 357–385, <http://arxiv.org/abs/1104.3784v1>
- [3] M. Buzio, Fabrication and calibration of search coils, in CERN Accelerator School CAS 2009: Specialised Course on Magnets, Bruges, 16–25 June 2009 (CERN, Bruges, 2009), pp. 387–421, <http://arxiv.org/abs/1104.0803v1>
- [4] K. N. Henrichsen, “Classification of magnetic measurement methods,” in CERN Accelerator School, Magnetic Measurement and Alignment, Montreux, 16–20 March 1992 (CERN, Montreux, 1992), pp. 70–83, <http://cdsweb.cern.ch/record/245401/files/p70.pdf>.
- [5] N. Smirnov, L. Bottura, M. Calvi, G. Deferne, J. DiMarco, N. Sammut, S. Sanfilippo, “Focusing Strength Measurements of the Main Quadrupoles for the LHC”, *IEEE Transactions on Applied Superconductivity*, vol. 16, no. 2, p. 261, June 2006
- [6] E. Todesco, B. Bellesia, L. Bottura, A. Devred, V. Remondino, S. Pauletta, S. Sanfilippo, W. Scandale, C. Vollinger, E. Wildner, “Steering Field Quality in the Main Dipole Magnets of the Large Hadron Collider”, *IEEE Transactions on Applied Superconductivity*, vol. 14, no. 2, June 2004
- [7] P. Arpaia, V. Inglese, G. Spiezia, Performance Improvement of a DSP-Based Digital Integrator for Magnetic Measurements at CERN, *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 7, p. 2132, July 2009
- [8] L. Bottura, M. Buzio, G. Deferne, P. Schnizer, P. Sievers, N. Smirnov, “Magnetic Measurement of Alignment of Main LHC Dipoles and Associated Correctors”, *IEEE Transactions on Applied Superconductivity*, vol. 12, no. 1, March 2002
- [9] J. Billan, L. Bottura, M. Buzio, G. D'Angelo, G. Deferne, O. Dunkel, P. Legrand, A. Rijllart, A. Siemko, P. Sievers, S. Schloss, L. Walckiers, "Twin rotating coils for cold magnetic measurements of 15 m long LHC dipoles," *IEEE Transactions on Applied Superconductivity*, vol.10, no.1, pp.1422-1426, 2000
- [10] N. R. Brooks, L. Bottura, J. G. Perez, O. Dunkel, and L. Walckiers, “Estimation of Mechanical Vibrations of the LHC Fast Magnetic Measurement System”, *IEEE Transactions on Applied Superconductivity*, vol. 18 no.2, p 1617, 2008.