20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Experimental characterization of a rotating coil transducer for local multipole scanning

P. Arpaia[1,2], M. Buzio[2], E. De Matteis[1,2], O. Dunkel[2], S. Russenschuck[2]

[1] *University of Sannio, Benevento, Italy, arpaia@unisannio.it; edematt@unisannio.it*
[2] *European Organization for Nuclear Research(CERN), Geneva, Switzerland, stephan.russenschuck@cern.ch*

***Abstract* – Recent compact accelerator developments for biomedical care and physics research has brought the need for small-aperture magnets as well as strongly bent magnet with curvature radii of less than 5 meters. Traditional transducers for magnetic measurements are not mechanically adaptable for local magnetic field measurements. In this paper, a new rotating coil transducer with compact design is proposed for local, transversal multipole scanning in straight and curved magnets. The requirements, design, prototyping, and the results of magnetic and electrical compatibility tests are presented.**

I. INTRODUCTION

A technical aspect, common to most recent accelerator projects, are straight and curved magnets with small apertures, resulting in a need for new magnetic measurement systems for a full characterization of the local, transversal field homogeneity. The majority of the measurement systems involves the use of specialized and thus not flexible systems. Measurement systems based on Hall probe transducers [1, 2, 3, 4, 5] are used for measuring magnets with straight aperture or bent magnets with open apertures [5, 6](C- shape magnets). In general, their measurement precision depends strongly on the positioning stability, difficult or impossible to be verified in situ, and with scarce flexibility to the new measurement needs arising from closed and large curvature magnets.

For integral field investigation and scanning of manufacturing defects, the main measurement systems are based on fixed or rotating coil transducers. At CERN, the main systems are the Dipole and Quadrupole Industry Magnetic Measurement (DIMM and QIMM) [8] and the Fast Measurement Equipment (FAME) [9]. The QIMM exploits a traveling rotating coil, called a mole [10], which is a transducer with 5 sensing coils, used in straight and large-aperture magnets (50 mm) at room temperature. The FAME system rotates a long coil shaft for acquiring the field in superconducting magnets at room or cryogenic temperatures. A local scan is not possible and only the integral field is measured; the system can thus not be applied to curved magnets.

In literature, most common measurement systems for curved magnets are based on fixed coil transducers. In [11], an array of printed coils (fluxmeters) measures the integral field and establishes the tolerance range of magnetic field in ramped field conditions. Long curved coil are presented in [12, 13] for scanning the aperture and evaluating the integral field. Non-local field investigation and non-fringe field analysis is difficult to carry out. In [14], a mole for testing curved superconducting magnets in cold conditions is presented.

The need for a new transducer design is increasing for local and fringe field investigation applied to straight- and curved-aperture magnets (aperture < 50 mm, curvature radius < 5 m) with the main requirement of the mechanical flexibility (cross section < 40 mm, length < 200 mm).

In this paper, a Scanning Rotating Coil Transducer with low weight and small size compared to the magnet aperture is proposed. For straight aperture magnet testing, the transducer allows local and integral measurement. In bent apertures, a local multipole analysis and an optimized fringe field evaluation can be made for both DC and pulsed (or ramped) magnets. In the following sections, the requirements, the design, and the implementation aspects of the proposed Transducer are highlighted. Finally, the experimental tests for technical feasibility in terms of magnetic and electrical compatibility are reported.

II. REQUIREMENTS

The main requirements arise from the need for local and fringe field measurements and the mechanical flexibility required by the different magnet apertures and magnet curvatures. The transducer must have small dimension and light weight for allowing easy motion and low position error. For local and integral measurements, the best sensor remains the rotating coil probe: according to recent developments on printed circuits [15], the coil can actually be made very compact.

Another important requirement of the transducer is to know its angular position in order to make possible the local multipole analysis in the DC magnets and to fix the position of coil for pulsed magnet measurements.

The above requirements highlight some technological aspects to be considered: magnetic compatibility, mechanical stability of all the components, and low electrical noise.

ISBN-14: 978-92-990073-2-7

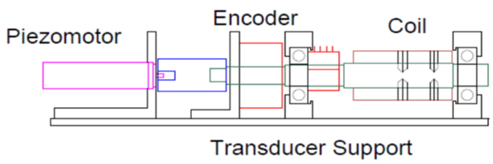

Figure 1: Architecture of the Scanning Rotating Coil Transducer.

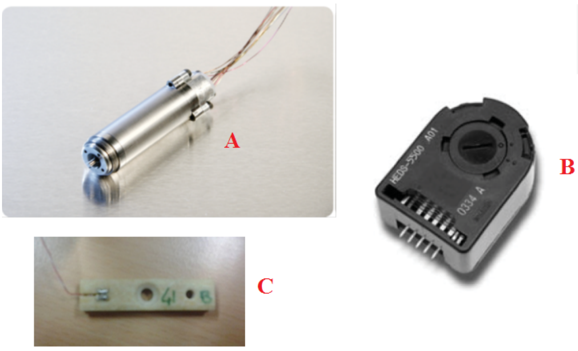

Figure 2: Main components of Scanning Rotating Coil Transducer prototype: A) piezomotor PAD7100 by Noliac, B) encoder HEDM505-J13 by Avago Technologies, and C) test coil of 40×10 *mm,* $S = 0.12367$ *m*^{2} *and* $R = 420\,\Omega$.

The magnetic compatibility of components is necessary for avoiding perturbation of the field throughout the measurement. Consequently, the new transducer should be free of ferromagnetic and highly conducting parts. In fact, these materials could generate field errors due to magnetization and eddy currents, and as a consequence, the occurrence of vibrations during the measurement. The manufacturing precision is fundamental for having low dimensional tolerances, and thus low vibration, with consequent low harmonic distortion in the acquired signal. Moreover, the electrical noise intrinsic to all the devices is to be controlled for the quality of the data acquisition.

III. TRANSDUCER DEVELOPMENT

In this section, the design and the prototyping of the Scanning Rotating Coil Transducer are presented.

A. *System design*

The above mentioned requirements were satisfied by the architecture shown in Fig. 1. The key is to choose compact and magnetically compatible components. Non-magnetic technology, like piezoelectric drives, were investigated. Optical encoders with plastic code wheels are the most compact and promise the best technical specifications (high counts per turn) and angular position. The coils must be compact, on the order of a few centimeters, and with a large total surface for acquiring the signal with low noise.

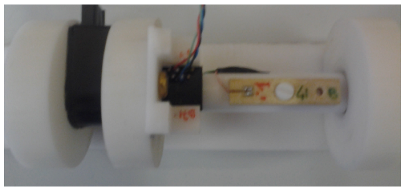

Figure 3: Support with coil shaft and electrical connection.

B. *Prototype manufacture*

As a drive system, a piezoelectric motor PAD7100 of Noliac [16] was adopted (see Fig. 2A). In addition to piezoelectricity, the main specifications of PAD7100 are the small physical dimension (diameter 12 mm, length 50 mm), its low weight (41 g), its variable speed of rotation ($90-180$ rpm), and sufficient torque (0.01 Nm). On the other hand, the presence of ferromagnetic material, in the screws and steel shaft of steel represents an aspect to check experimentally. The optical encoder HEDM 5505-J13 of Avago Technologies [17] (Fig. 2B) has specifications matching the design goals: non-magnetic material (plastic code wheel), compact dimension ($41 \times 30 \times 18$ mm), and 1024 cycles per revolution. Two coils (Fig. 2C) of dimensions 40×10 mm, with a total sensing surface of 0.12367 m^2, number of turns 485, and resistances $R = 420\,\Omega$ are mounted on the shaft (Fig. 4). However, the choice of coils depends on the magnetic field strength, and can be easily adapted. In Fig. 3, the general support in plastics and the coil connection by slip rings are shown. Regarding the support structure, the motor is fixed to another base place in order to easily exchange and test other drive units.

IV. EXPERIMENTAL CHARACTERIZATION TESTS

In the following, the preliminary tests of magnetic compatibility and electrical interference of the prototype are described.

A. *Magnetic Compatibility Test*

This test is aimed at establishing the perturbation threshold boundary of the transducer. After having checked the materials of each component, the only element with ferromagnetic parts is the piezomotor PAD7100. The test procedure is to insert the motor unit in an accelerator magnet (DC field), and to record the field change with an NMR probe. This test was repeated with different orientations (Fig. 4) of the motor with respect to the NMR probe, at increasing field levels (0.4, 0.5, 0.8 T), and with the motor switched off and on. The objective is to establish the distance where the perturbation drops below a level of 10^{-4}. The measurement setup is composed by a NMR Teslameter (Metrolab PT2025 [18]), the dipole reference magnet MCB22 of the Magnetic Measurement Section at CERN,

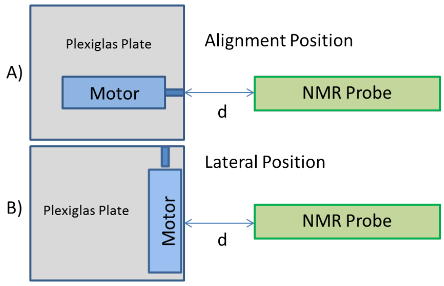

Figure 4: Measurement setup for magnetic compatibility test: A) motor aligned with NMR probe, and B) motor positioned laterally to NMR probe.

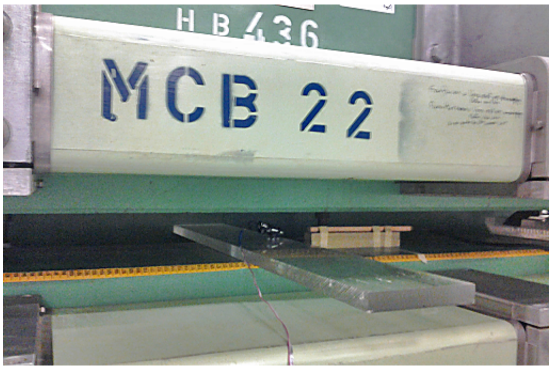

Figure 5: Magnetic compatibility test: plexiglas support of the motor and the NMR probe inside the MCB22 reference dipole.

and the device under test, i.e., the piezomotor PAD7100 (Fig. 5). In the worst case, that is, the test at 0.8 T in alignment position according to Fig. 4A, the magnetic field measured by the NMR teslameter without motor is of 0.800108 T. In Tab.1, the differences of magnetic field measured by NMR probe with motor (off and on) at different distances is given. Fig. 6 shows the graph of the relative differences between the magnetic fields measured with and without motor, and the perturbation reference tolerance. The distance identified by the test is 7 cm, for the presence of ferromagnetic materials inside the motor to have negligible influence on the field measured.

Table 1: Relative differences of magnetic field between the reference NMR measurement (without motor) and the ones with motor (off and on) at 0.8 T and different distances.

d [cm]	Δ(mot. off)	Δ(mot. on)
3	0.000682	0.000619
4	0.000321	0.000292
5	0.000145	0.000139
6	0.000127	0.000122
7	0.000044	0.000030

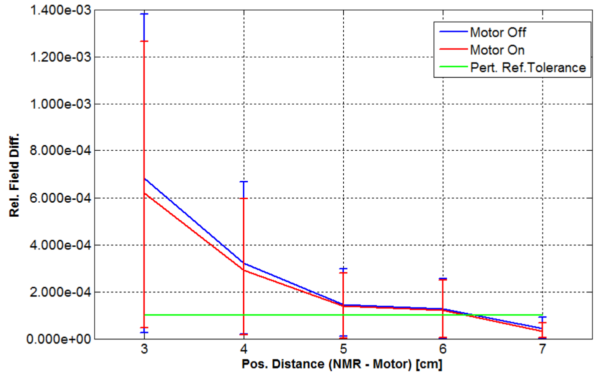

Figure 6: Relative variations of magnetic field without and with motor (off and on) in alignment position.

B. Electrical Interference Test

The measurement setup (shown in Fig. 7) is based on the prototype (rotating motor, encoder, and rotating coil shaft), an independent fixed coil (dim. 20 × 10 mm, $S = 0.31839$ m^2) and a data acquisition card (NI PXI 6289 [19]). The test procedure is to acquire the output voltage of the fixed coil over the full speed range of the motor, for different relative positions and distances of the fixed coil. The aim is to measure the peak amplitude of the induced noise of the prototype as a whole and to understand its influence on the measured voltage signal of the rotating coil. Different configurations between prototype and fixed coil were tested to analyze the interference. The results presented here are referred to two interesting cases: i) fixed coil planar and parallel to the prototype, by acquiring the voltage signal for different rotation speeds, and ii) planar and perpendicular to the prototype, by acquiring the voltage signal at different positions (with respect to the motor, encoder, and rotating coil).

For both configurations, three different states were evaluated: 1) motor off, 2) motor and encoder on, and 3) encoder off. In this way, the tests were able to distinguish the electrical interference of each component. Four acquisitions of 2 s and 400.000 samples each were considered for each state (sampling frequency of 200.000 S/s, improving the resolution of the data acquisition card, $\delta R = \pm 0.01$ μ V). The standard deviation and mean of the fixed coil voltage signal is calculated to measure the electrical noise contribution, by avoiding offset and DC voltages. In case of the first configuration (Fig. 7A), the rotary speed of the prototype is controlled by the Noliac NDR8210[16] setting the oscillation frequency signal of the piezoelectric elements. The chosen frequencies are 20,30 and 40 Hz, for 5, 7 and 10 rpm, respectively. The results in Tab. 2 show increasing noise with the rotating speed (Fig. 8). In the second configuration (Fig. 7B), the results of Tab. 3 and

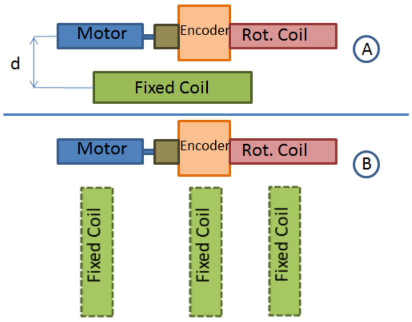

Figure 7: Configurations of electrical interference test: with fixed coil A) parallel and B) perpendicular to the prototype.

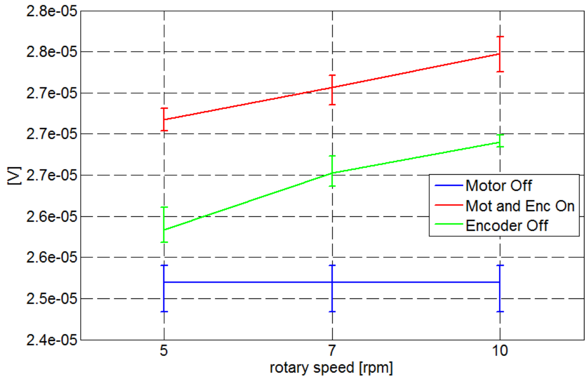

Figure 8: Standard deviation and its spread over 4 consecutive measurements of fixed coil voltage signal for different rotary speeds.

Fig. 9 show a greater electrical interference close to the motor. Finally, in both cases, the absolute values of the electrical interference are less than 30 μV at distances of 4.5 and 3 cm. Considering an acceptable threshold of 10^{-4} for a typical coil voltage of 1 V, the measured electrical interference will fall within this threshold.

V. CONCLUSION

A rotating coil transducer was proposed for local multipole scanning in the curved and small aperture accelerator magnets. For this reason, the transducer exhibits a very compact design to satisfy the technical requirement of mechanical flexibility. The experimental characterization of the first prototype verified the technological requirements of magnetic compatibility and the low electrical noise. The first test concerned the magnetic components of the motor, save region identified for magnetic compatibility is at a radius larger than 7 cm. In the second test, the acceptable lower bound of voltage (100 μV) for quantifying the electrical noise interference was evaluated in a radius of about 4 cm. In conclusion, the removal of any martensitic phases in the motor components is crucial for having a very-compact transducer and, consequently, for reducing the magnetic perturbation and achieving a satisfying resolution in local magnetic field scanning. Rotation quality and endurance tests will complete the feature investigation of the proposed prototype.

Table 2: Standard deviation of fixed coil voltage for different rotary speeds in three states: motor off (Off), motor and encoder on (On), and encoder off ($d = 4.5$ cm).

Rot.[rpm]	Off [μV]	On [μV]	Enc.Off [μV]
5	25, 20	27, 17	25, 84
7	25, 20	27, 57	26, 52
10	25, 20	27, 98	26, 90

Table 3: Standard deviation of fixed coil voltage for different perpendicular position in three states: motor off (Off), motor and encoder on (On), and encoder off (Fig.7(B)).

Pos.	Off [μV]	On [μV]	Enc.Off [μV]
M	26, 96	29, 62	28, 62
E	18, 73	21, 98	19, 27
S	17, 21	21, 55	17, 27

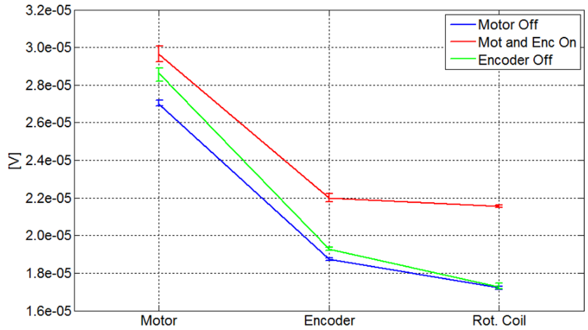

Figure 9: Standard deviation and its spread over 4 consecutive measurements of fixed coil voltage signal for different perpendicular positions (see Fig. 7B).

ACKNOWLEDGMENTS

The authors thank the Noliac Company for providing the prototype piezoelectric motor PAD7100. We also thank the technical engineers of CERN's magnetic measurement section for their assistance.

REFERENCES

[1] J. Campmany et al., "Looking for a Hall probe bench for closed big magnetic structures", IMMW17 - International Magnetic Measurement Workshop La Mola, Terrassa-Barcelona, Catalonia (Spain), 18-23 Sep. 2011.

[2] C. W. Ostenfeld, "Measurements of Max-IV girder systems", IMMW18 - International Magnetic Measurement Workshop, Brookhaven National Laboratory Upton, New York, USA, Jun. 2013.

[3] M. Negrazus et al., "Magnet Design and Measurement Results of the Solenoids and Bunch Compressor Bending Magnets of the SwissFEL Test Facility", IEEE Trans. on Applied Superconductivity, Vol. 22, No. 3, Jun. 2012.

[4] A.M. Batrakov et al., "Nine tesla superconducting-bending magnet for BESSY-II", Nuclear Instruments and Methods in Physics Research A, vol. 543, (2005) pp. 35-41.

[5] J. Muratore et al., "Magnetic Field Measurements of an HTS Retrofit Synchrotron Dipole", IEEE Trans. on Applied Superconductivity, Vol. 21, No. 3, Jun. 2011.

[6] A. Batrakov et al., "Bending magnets for the SAGA Storage Ring", Nuclear Instruments and Methods in Physics Research A, Vol.543, (2005), pp. 47?50.

[7] M. Negrazus et al., "The Fast Ramped Bending Magnets for the Gantry 2 at PSI", IEEE Trans. on Applied Superconductivity, Vol. 18, No. 2, Jun. 2008.

[8] J. Garcia Perez, J. Billan, M. Buzio, P. Galbraith, D. Giloteaux, and V. Remondino, "Performance of the Room Temperature Systems for Magnetic Field Measurements of the LHC Superconducting Magnets", IEEE Transactions on Applied Superconductivity, Vol. 16, No. 2, June 2006.

[9] P. Arpaia, M. Buzio, L. Fiscarelli, G. Montenero, J. Garcia Perez, L. Walckiers, "Compensation of Third-Harmonic Field Error in LHC Main Dipole Magnets", Instrumentation and Measurement Technology Conference (I2MTC), 2010 IEEE, Austin TX, USA, 3-6 May 2010.

[10] Bottura, L., et al., "A mole for warm magnetic and optical measurements of LHC dipoles", IEEE Transactions on Applied Superconductivity, Vol. 10, No. 1, pp. 1454 - 1457, March 2000.

[11] G. Golluccio et al., "Overview of the magnetic measurements status for the MedAustron project", 18th International Magnetic Measurement Workshop (IMMW18), Brookhaven, June 3-7,2013.

[12] Hanno Leibrock et al., "Prototype of the Superferric Dipoles for the Super-FRS of the FAIR-Project", IEEE Transactions on Applied Superconductivity, Vol. 20, No. 3, June 2010.

[13] W. Chen et al., "A Flipping-coil Field Measurement System for the CSNS/RCS Dipole Magnet ", 18th International Magnetic Measurement Workshop (IMMW18), Brookhaven, June 3-7,2013.

[14] P. Schnizer et al., "Mole for Measuring SIS100 Magnets Commissioning and First Test Results", IEEE Transactions on Applied Superconductivity, Vol. 20, No. 3, June 2010.

[15] J. Di Marco, " Application of PCB and FDM Technologies to Magnetic Measurement Probe Development", 18th International Magnetic Measurement Workshop (IMMW18), Brookhaven, June 3-7, 2013.

[16] Noliac A/S 2011, NOLIAC, available: http://www.noliac.com/

[17] Avago Technologies Group, Optical Encoder HEDM 5500-J13, Available: http://www.avagotech.com.

[18] Metrolab, "NMR Precision Teslameter PT2025", available: http://www.metrolab.ch/

[19] National Instruments, "NI PXI 6120", available: http://www.ni.com/