19th Symposium IMEKO TC 4 Symposium and 17th IWADC Workshop
Advances in Instrumentation and Sensors Interoperability
July 18-19, 2013, Barcelona, Spain

Multipole-field correction of stretched-wire measurements of the gradient in accelerator magnets

P. Arpaia[1], C. Petrone[1,2], S. Russenschuck[2], L. Walckiers[2]

[1] *Department of Engineering, University of Sannio, Corso Garibaldi 107, 82100 Benevento, Italy*
E-mail: arpaia@unisannio.it
[2] *CERN, Department of Technology, Group of Magnets, Superconductors and Cryostats (MSC), Section of Magnetic Measurements, 1211 Geneva 23, Switzerland*

Abstract- A measurement system for the correction of gradient-field measurements using stretched wires is described. Relative field multipoles of a magnet are measured through the oscillating-wire technique. Then, by means of the same setup, the multipoles are used to correct the gradient measurements with the stretched wire technique. In this paper, after an analytical background on stretched and oscillating wire methods, the proposed correction is described. Preliminary results of experimental validation of the proposed correction on measurements of a quadrupole for the CLIC accelerator study at CERN are illustrated.

Keywords: Electromagnetic Fields, Vibration Measurement, Measurement Science, and Force Measurement.

I. Introduction

The Single-Stretched Wire (SSW) method is commonly used to measure the magnetic field strength and axis [1]-[2] in accelerator magnets. Displacing the wire in the magnet in radial direction and integrating the induced voltage yield the intercepted magnetic flux, and, consequently, the strength of the magnetic flux density:

$$\psi = \iint_{\mathbb{A}} \vec{B}(\mathrm{r}) \cdot d\vec{a} = \oint_{\partial \mathbb{A}} \vec{A} \cdot dl, \tag{1}$$

where $\vec{B}(\mathrm{r})$ is the magnetic flux density, $d\vec{a}$ is an element of the surface $\mathbb{A}$, and $\vec{A}$ is the vector potential. The integrated magnetic flux density $\vec{B}$ of accelerator magnets can be expressed by the 2-dimensional series expansion with Fourier coefficients B_n and A_n known as field harmonics [3]:

$$\vec{B} = B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{\mathbf{z}}{\mathrm{r}_0}\right)^{n-1}. \tag{2}$$

where the coefficients are defined on the complex plane $\mathbf{z} = x + iy$ and can be combined in the complex notation $B_n + iA_n = \mathbf{C}_n$, and r_0 is an arbitrary reference radius, usually chosen at 2/3 of the magnet's aperture. The linked flux is independent on the path the wire takes from the initial position $\mathbf{z}_1$ to the final position $\mathbf{z}_2$. For movements from the magnetic centre to a position x along the horizontal axis, that is, $\mathbf{z}_1 = (0 + i0)$ and $\mathbf{z}_2 = (x + i0)$, substituting (2) in (1) yields:

$$\psi = L_m \sum_{n=1}^{\infty} \frac{B_n}{(r_0)^{n-1}} \frac{x^n}{n}. \tag{3}$$

where L_m is the magnetic length.

II. Proposal

In the following, the correction of the quadrupole field gradient measured by the stretched wire by considering the higher-order multipole components is described. The method takes advantage of the two measurements (stretched and oscillating wire) carried out without unmounting the magnet or the stages from the bench. A method for measuring multipoles of the magnetic field by means of an oscillating wire was proposed in [4].
A method to find the magnetic axis as a starting point is to minimize the oscillation amplitude of the wire powered in its resonance frequency [5]. Moving the wire along the mid plane from $\mathbf{z}_1 = (x + i0)$ to $\mathbf{z}_2 = (-x + i0)$, Eq. (3) yields the following relation:

$$\psi_{+x} + \psi_{-x} = L_m \cdot \left[\sum_{n=1}^{\infty} \frac{B_n}{(r_0)^{n-1}} \frac{(x)^n}{n} + \sum_{n=1}^{\infty} \frac{B_n}{(r_0)^{n-1}} \frac{(-x)^n}{n}\right]. \tag{4}$$

When (4) takes its minimum, the flux linkage is zero and therefore the motion is symmetric to the magnetic axis. As the displacement, x in Eq. (4), is increased the higher-order terms because more important and yield to a wrong estimation of the field gradient. For a quadrupole magnet with the main component B_2 Eq. (4) can be

written as:

$$\psi_{+x} + \psi_{-x} = g \cdot \left[\frac{\sum_{n=1}^{\infty} \frac{B_n}{(r_0)^{n-1}} \frac{(x)^n}{n} + \sum_{n=1}^{\infty} \frac{B_n}{(r_0)^{n-1}} \frac{(-x)^n}{n}}{\frac{B_2}{(r_0)^{2-1}} \frac{(x)^2}{2}} \right], \tag{5}$$

with the gradient:

$$g = L_m \cdot \frac{B_2}{(r_0)^{2-1}} \frac{(x)^2}{2} \quad \left[\frac{T}{m} m \right], \tag{6}$$

which is related to the field components by $B_y = g\,x$ and $B_x = g\,y$. For the relative multipoles in the quadrupole defined by:

$$c_n = 10^4 \cdot \left(\frac{C_n}{B_2} \right) = 10^4 \cdot \left(\frac{B_n + iA_n}{B_2} \right) = b_n + ia_n, \tag{7}$$

we obtain:

$$\psi_{+x} + \psi_{-x} = g \cdot \sum_{n=1}^{\infty} \frac{10^{-4} \cdot b_n}{n} \left[\frac{(x)^{n-2} + (-x)^{n-2}}{(r_0)^{n-2}} \right] = g \left\{ 1 + \frac{10^{-4} \cdot b_4}{2} \left(\frac{x}{r_0} \right)^2 + \frac{10^{-4} \cdot b_6}{3} \left(\frac{x}{r_0} \right)^4 + \cdots \right\} \tag{8}$$

Therefore, the measured flux, acquired by means of the single-stretched-wire system, can be corrected for the effect of the higher-order multipoles measured by means of the oscillating wire system:

$$g = \frac{\psi_{+x} + \psi_{-x}}{1 + \frac{10^{-4} \cdot b_4}{2} \left(\frac{x}{r_0} \right)^2 + \frac{10^{-4} \cdot b_6}{3} \left(\frac{x}{r_0} \right)^4 + \frac{10^{-4} \cdot b_8}{4} \left(\frac{x}{r_0} \right)^6 + \cdots} \tag{9}$$

Moving the wire in the vertical plane, that is, from $z_1 = (0 + iy)$ to $z_2 = (0 - iy)$ the real part of the integral in Eq. (3) results a sign-change in the even numbered multipoles with respect to Eq. (9).

I.   Experimental validation

Results of the magnetic measurements performed on a model magnet [6] for the final focus transport line of the Compact Linear Collider (CLIC) at CERN, a site independent feasibility study for an electron-positron Linear Collider up to the multi-TeV center of mass colliding beam energy range, are presented as a case study. This high-gradient, hybrid quadrupole has a yoke length of 0.1 m and an aperture of 8.3 mm. Permanent magnet blocks provide a gradient of 85.6 T/m. The gradient can be increased to 509 T/m, when the magnets is excited to 18.6 A. The strength of the field was measured by the single-stretched-wire system and the multipole field-errors by means of the oscillating wire system.

The wire used can be considered free of permeable material [7]; it is passed through the magnet aperture and stretched by means of a motor. For the stretched wire measurement, a Fast Digital Integrator (FDI) [8] was used to acquire the signal. For the oscillating wire, measurement optocouplers in x and y directions are positioned on the stage in order to transduce the wire displacement into an electrical voltage. The sensor output, pre-amplified and low-pass filtered by an antialiasing filter, is then sent to the 18-bit acquisition system NI6289 from National Instruments[TM]. The same system also acquires the wire current on a reference resistor. A sinusoidal current in the measuring wire drives oscillation amplitudes measured by synchronous demodulation. The AC current generator Keithley[TM] 6221 is used to excite the wire.

The measurements require working at a current frequency lower than the wire mechanical resonance. Although giving rise to higher measurement sensitivity, the amplitude of the wire vibration in resonance condition is more prone to environmental influences and on the damping conditions.

A motor controller Newport[TM] ESP7000 is used for moving the stages, reading the position through a linear encoder with a precision of ±0.1 µm. The test software is implemented by means of the Flexible Framework for Magnetic Measurements (FFMM) [9]. The possibility to carry out measurements at different reference radii by means of the same hardware yields a high flexibility useful to validate magnet prototypes of different apertures. The field multipoles are finally computed by the analysis procedure described above, implemented in Matlab[TM]. Multipoles shown in Fig. 1 in logarithm scale at different current have been measured at a 3 mm reference radius. All measurement were performed after centring the magnet to better than 0.01 mm so that the correction from feed-down from higher multipoles has not been performed. While the allowed multipoles b_6, b_{10}, b_{14} show relatively large values, the small values of the non-allowed multipoles (which can only occur in accelerator magnets due to manufacturing tolerances and deviations from the quadrupolar symmetry) show large relative measurement errors for orders larger than ten. Above the order of ten, the measured multipoles do no more obey the Cauchy estimate for multipole coefficients of bounded and smooth periodic signals.
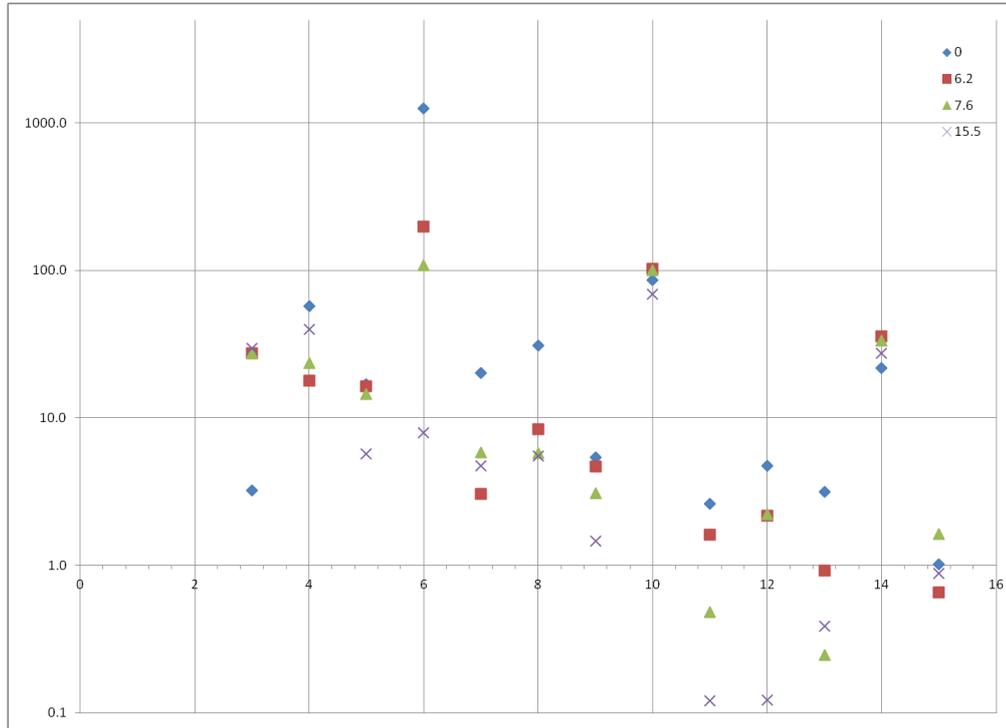
Figure 1. Normal relative Multipoles (b_n, in 10^{-4} units) in log scale as a function of current (A) at r_0 = 3 mm.

In Tab. 1, the integrated gradient is represented as a function of the excitation current. Using the multipole field measurements up to order six, the gradient is corrected by means the proposed correction.

			NOT CORRECTED			CORRECTED
I (A)	GDLx	GDLy	Abs (GdL Y)-Abs(GdL X)/Abs (GdL X)	GDL x (T)	GDL y (T)	Abs (GdL Y)-Abs(GdL X)/Abs (GdL X)
0.0	9.245	-9.327	0.009	8.886	-8.907	0.002
6.2	32.686	-32.786	0.003	32.557	-32.618	0.002
7.6	39.174	-39.274	0.003	39.144	-39.177	0.001
15.5	51.358	-51.462	0.002	51.504	-51.430	-0.001
7.6	39.523	-39.618	0.002	39.498	-39.530	0.001
6.2	33.077	-33.164	0.003	32.959	-33.002	0.001
0.0	9.238	-9.307	0.007	8.880	-8.883	0.000

Table 1. Measurement of the integrated gradient (T) with the SSW after correction from the measured multipole.

II.   Conclusions

A method based on wire techniques for correcting higher-order field errors in gradient measurement is proposed. Using the same setup, and without realigning the magnet and the wire stages, three different techniques are applied: (i) vibrating wire, for the location of the magnetic axis, (ii) oscillating wire, for the multipole field errors, and (iii) the single-streched wire, for the field strength along the horizontal and vertical planes. The method yields a high flexibility with respect to magnet lengths and magnet apertures. As an experimental case study, the measurements of a hybrid quadrupole magnet for the CLIC study are presented.

References

[1] D. Zangrando, Richard P. Walker, "A stretched wire system for accurate integrated magnetic field measurements in insertion device", *Sincrotrone Trieste, Padriciano 99*, 34012 Trieste, Italy.
[2] G. Deferne, M. Buzio, N. Smirnov and J. DiMarco, "Results of magnetic measurements with the Single Stretched Wire (SSW) System on a LHC prototype main lattice quadrupole and LHC preseries dipoles". *13th*

International Magnetic Measurement Workshop, May 19-22, 2003, Stanford, California.

[3] S. Russenschuck, *Field Computation for Accelerator Magnets*, 2010 WILEY-VCH.

[4] P. Arpaia, M. Buzio, J. Garcia Perez, C. Petrone, S. Russenschuck and L. Walckiers. "Measuring field multipoles in accelerator magnets with small-apertures by an oscillating wire moved on a circular trajectory". *Published By IOP Publishing For Sissa Medialab,* May 2012. Doi: 10.1088/1748-0221/7/05/P05003.

[5] P. Arpaia, C. Petrone, and L. Walckiers. "Experimental validation of solenoid magnetic centre measurement by vibrating wire system". *XX IMEKO World Congress Metrology for Green Growth*, September 9–14, 2012, Busan, Republic of Korea.

[6] M. Modena, O. Dunkel, J. Garcia Perez, C. Petrone, E. Solodko, P. Thonet, D. Tommasini, A. Vorozhtsov, "Design, assembly and first measurements of a short model for CLIC final focus hybrid quadrupole QD0". *IPAC2012*, New Orleans, Louisiana, USA, THPPD010.

[7] Guy Deferne, Nikolay Smirnov, Joe DiMarco, "Enhancement of Single Stretched Wire Measurements of LHC Short Straight Sections", *14th International Magnetic Measurement Workshop – IMMW*14, 26-29 September 2005, Geneva, Switzerland.

[8] P. Arpaia, L. Fiscarelli, N. Cardines, C. Petrone. "Design of an on-line dynamic magnetic flux analyzer based on double-buffer sliding DFT". *17th Symposium IMEKO TC 4, 3rd Symposium IMEKO TC 19 and 15th IWADC Workshop Instrumentation for the ICT* , Sept. 8-10, 2010, Kosice, Slovakia.

[9] P. Arpaia, L. Fiscarelli, G. La Commara, C. Petrone. "A Model-Driven Domain-Specific Scripting Language for Measurement System Frameworks". *IEEE Transactions On Instrumentation And Measurement*, VOL. 60, NO. 12, December 2011.