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In-situ calibration of rotating coil magnetic measurement systems: a case study on Linac4 magnets at CERN

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Abstract- An in-situ procedure for calibrating the equivalent radius and width of the coil transducer in rotating mode measurements for magnetic field quality analysis is proposed. The standard calibration procedure is not suitable when the coil is longer than the magnet under test, because an average value of the radius and of the width along the length as a whole is obtained. This problem increases for small coils used in small-aperture magnets, such as quadrupoles of new-generation linear accelerators. In the paper, the problem of the coil parameter calibration is highlighted and then the proposed calibration method and the corresponding measurement station are illustrated. Experimental results of a case study on the magnet series of the new linear particle accelerator LINAC4, designed to intensify the proton flux currently available in the accelerator chain at the European Organization for Nuclear Research (CERN), are reported.

I. Introduction

The most accurate technique of field quality measurement for particle accelerator magnets is based on a transducer coil rotating into the magnet apertures [1]. A measurement of the magnetic flux linked to the rotating coil as a function of the angular position is delivered. The main quantities of interest for field quality characterization are the harmonic coefficients of the 2D field expansion [2]. Those coefficients depend essentially on the length, the width and the rotation radius of the coils. By means of mechanical measurements practically only the length can be obtained accurately enough ($\pm 10^{-3}$~10^{-4}). Magnetic measurements are the best option because all non-idealities are automatically included in the results [3]. The equivalent width and radius have to be determined by rotating the coil in a known uniform dipole field and in a uniform quadrupolar magnetic field respectively. The classical approach to the coil calibration [4], using an uniform magnetic field over the whole coil length, gives an average value for the radius and width which is suitable when the coil is shorter than the magnet under test or in the ideal case of perfectly constant width. This procedure fails when the coil geometry is not regular, and the mechanical errors become more influent when the coil size is reduced. At CERN, a new linear accelerator Linac4 is currently being built to replace the old Linac2. The transverse focusing to the beam is given by several Permanent Magnet Quadrupoles (PMQ) [5] with an aperture 22 mm and 450 mm length. The small dimensions of the support used to build up the coil (in this case 200 mm of length, less than 10 mm in width and 1 mm thickness) make the winding process more difficult. Low rigidity in the winding can easily occur at the end side and in the middle of the coil.

In this paper, first the theoretical background of the rotating coil magnetic measurement is illustrated, focusing on the coil sensitivity parameter calculation. In section II, the proposed coil calibration method is shown in the specific case of a quadrupole magnet. The last section will report about the measurement station and the experimental results on Linac4 PMQs.

II. Rotating coil background

In the classical 2D harmonic analysis, the field harmonic content is proportional to the DFT coefficients Ψ_n of the flux samples Φ_k as a function of the angular position:

$$\Psi_n = \sum_{k=1}^{N} \Phi_k e^{-2\pi i (n-1)\frac{(k-1)}{n}} \tag{1}$$

From eq. (1), the magnetic field harmonic coefficients C_n are derived [2]:

$$C_n \approx \frac{2}{N}\frac{R_{ref}^{n-1}}{\kappa_n}\Psi_{n+1} \qquad (2)$$

where R_{ref} is the reference radius (typically the transverse size of the particle beam), N is the number of angular points per turn and κ_n are complex geometric calibration coefficients or coil sensitivity factors. These represent the coil geometry completely, and they are independent of the measured magnetic field. For a perfect radial coil, initially on the horizontal plane (zero initial phase), with an infinitesimally thin winding cross-section, the factors reduce to a real number [3]:

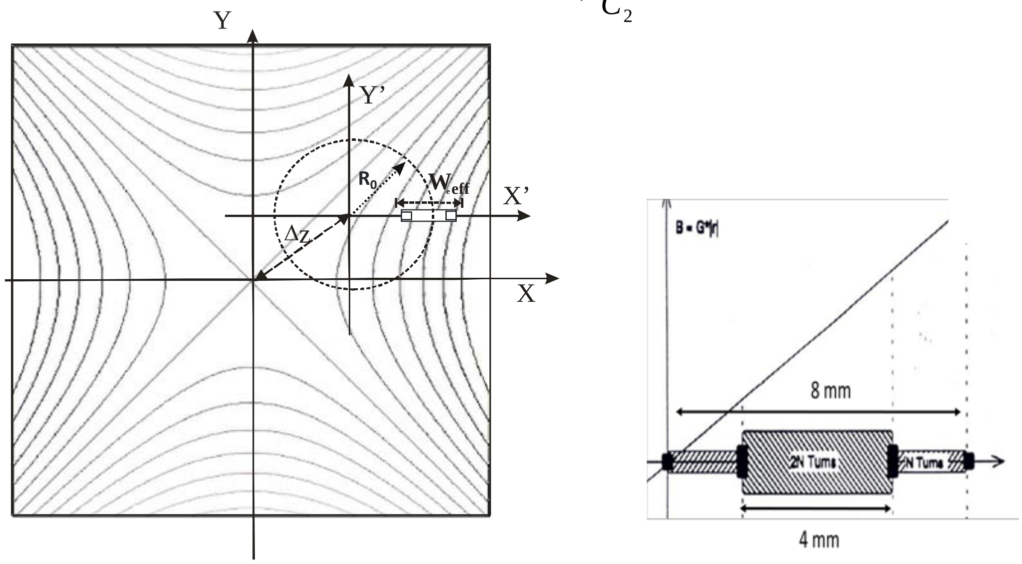
$$\kappa_n = \frac{N_T L_c\left[\left(R_0 + \frac{W_{eff}}{2}\right)^n - \left(R_0 - \frac{W_{eff}}{2}\right)^n\right]}{n} \qquad (3)$$

where R_0 is the average radius, L_c is the length of the coil, n is the harmonic order, N_T is the number of coil turns and W_{eff} is the width of the coil. In other words, the coil sensitivity factors for a radial coil can be computed from the total equivalent area A_c of the coil (given by the length, the width and the number of turns) and the equivalent radius R_0 (average between the two coil ends).

All κ_n are proportional to total coil area A_c and increase like radius R_0^{n-1} and increase with W_{eff}^n. In the standard case A_c is estimated magnetically rotating the coil in a uniform known reference dipole and R_0 in a reference quadrupole once fixed the length of the coil by means of geometrical measurements [3].

The harmonic coefficients of eq. (3) are referred to the coil reference axes defined by the zero reference of the angular encoder [1]. A translation and a rotation in the 2-D complex plane are necessary to refer the harmonic coefficients to the magnet reference frame [6]. The distance vector $\Delta z = \Delta x + i\Delta y$ between the coil reference frame and the magnet reference frame (figure 1), which for a quadrupole magnet is centred on the magnetic axis where B=0, can be calculated from [2]:

$$\Delta z = -R_{ref}\,\frac{C_1}{C_2} \qquad (4)$$



a) b)

Figure 1: a) radial coil rotating in a quadrupole field. Y-X is the magnet frame, Y'-X' is the coil frame. b) details of the compensation scheme with two nested radial coils, the inner coil has half of the width W_{eff} but has the double the number of turns.

II. In-situ coil calibration method

A. Calibration Method

When the coil width irregularities are important and only a part of the coil is immersed in the magnetic field, the general method described above must be completed magnet under test instead of the standard references ("in-situ" calibration). In principle, if the magnet is moved transversally by a given distance and the quadrupole component C_2 is known, the radius R_0 and the equivalent width W_{eff} of the coil can be reconstructed directly. In other words, the two parameters can be computed by calculating κ_1 and κ_2 from eq. (3) and substituting them in eq. (2):

$$\begin{cases} C_1 = \dfrac{2\Psi_2}{NN_T L_c W_{eff}} \\ C_2 = \dfrac{2\Psi_3}{NN_T L_c W_{eff} R_0} \end{cases} \tag{5}$$

Assuming for instance a purely horizontal movement Δx, from (4) and (5), if the phase error between the coil frame and the magnet frame is negligible, R_0 can be derived:

$$R_0 = -\Delta x \,\mathrm{Re}\left\{\frac{\Psi_3}{\Psi_2}\right\} \tag{6}$$

The magnet strength, corresponding to the integrated quadrupole gradient (GdL), is used to calibrate the W_{eff}:

$$GdL = \frac{C_2}{R_{ref}} L_c \tag{7}$$

and:

$$w_{eff} = \frac{\mathrm{Re}\{\psi_3\}}{GdLR_0} \tag{8}$$

The reference value of the gradient *GdL* must be obtained in this method by an independent measurement.

III. Experimental Results

The coil used to measure this magnet is 200 mm long with an external diameter of 19 mm. It presents two nested radial windings on the same plane (figure 1 b). The external one generates the absolute signal relative to the main field of the quadrupole. The inner one is connected in series opposition to the external coil, in order to generate a signal more sensitive to the high order harmonics [1]. When the two coils are connected in electrical opposition the κ_1 of the series, as well the κ_2, are zero. This relation can be obtained only if the two coils have the same equivalent surface, thus the internal winding, since it has half of the W_{eff}, it has twice the number of turns.

A. Measurement station architecture

In Figure 2, the equipment used to calibrate the coil directly on the measurement system is depicted. The angular reference of the encoder is preliminarily aligned to the gravity by means of a sensor tilt on the shaft. A 2-D translation stage, equipped by a linear encoder of 0.3 μm resolution and 2 μm repeatability, allows the permanent quadrupole to be moved in the x-y direction. The angular error and the offset of the axes origins between the magnet reference frame and the 2-D stage were found by moving the magnet first along the x, then in y direction [7] and measuring the displacement Δz from eq.(4). The angular error of 0.5 ° and the origin displacement of 3 μm in the x direction and of 6 μm in y will not affect the calibration procedure. The measurement system is a new rotating bench aimed at testing the PMQ magnets of the Linac4 drift tube [5].

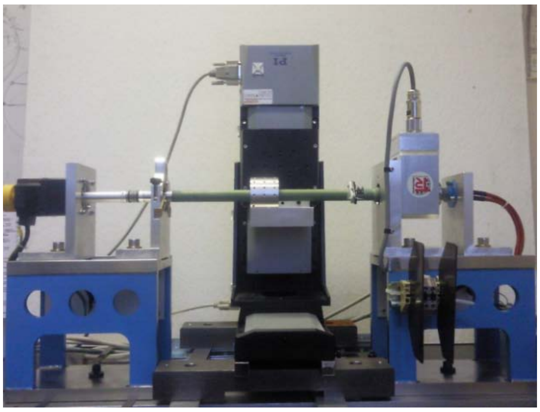


Figure 2: the rotating coil and the calibration system.

B. Measurement procedure

With the help of the 2D stage, the magnet is first centred with respect to the rotating coil by minimizing iteratively eq. (5). The coil radius and the equivalent width can be measured in 4 steps:

i) move the magnet along the x axis to a given position;
ii) make a continuous rotation measurement of the flux as a function of the angular position;
iii) calculate the FFT obtaining the 2^{nd} and the 3^{rd} harmonic of the measured flux (from (5), a movement in the *x* axis corresponds to a variation in the real part of the C_1, and a movement in the coordinate *y* affects the imaginary part of the 2^{nd} harmonic coefficient);
iv) calculate the R_0 from eq. (7) and W_{eff} from eq. (9).

C. Results

The procedure was applied to the Linac4 shaft using a prototype permanent quadrupole measured with the stretched wire system. The SSW [8] measured an integrated gradient of 2.435 Tm/m for this magnet. The longitudinal position was fixed at 110 mm from the left coil edge, where the width variation is linear and is far from the coil end side. The repeatability of the radius and of the coil area is better than $\pm$ 10 µm. The uncertainty of the two parameters calculated propagating the error from eq. (6) and (8) is $\pm$ 22 µm for the radius and $\pm$ 26 µm for the equivalent width.

The external coil is affected in the central part by a strong variation in the width profile. The internal coil is nested in the external one, thus its width is more uniform. Nevertheless, the radius variation with respect to the axis rotation reduces the uniformity of the measurement (the variation in the measurement is about $\pm$5 % along the 200 mm of the external coil length and of $\pm$3 % for internal coil). The accuracy of the gradient measurement is within the specifications only for the calibrated coil regions (better than 0.3 %, with respect to the required 1%). Once the coils are calibrated in a specific longitudinal position using the reference magnet, the calculated κ_n are exploited to evaluate the magnetic strength and harmonic quality of several quadrupoles of the Linac4 drift tube tank. The quadrupole strength measured is within the tolerances of $\pm$0.5% required from the beam optic specification, even if the uncertainty of the rotating coil measurement ($\pm$ 0.008 Tm/m) is higher than the one of the stretched wire ($\pm$ 0.002 Tm/m).

II. Conclusions

In this paper, a novel procedure to calibrate directly in situ the coil sensitivity geometry parameter is proposed. This procedure represents an improvement with respect to the standard one, which returns an average value of the coil radius and width along the whole length of the coil, is not accurate enough when the magnetic length is shorter than the coil length and the coil surface geometry is poor. The new procedure is applied to the prototype coils developed to measure the field quality of six permanent quadrupoles of the Linac4 drift tube. The RMS error of the magnetic strength measurement, compared to the stretched wire system taken as the reference, is improved from 6 % to 0.1%. Since the tolerance required for the accelerator is 1%, the new procedure can be used with confidence to avoid systematic measurements with the stretched wire system.

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