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Rotating-coil calibration in a reference quadrupole, considering roll-angle misalignment and higher-order harmonics

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ABSTRACT

A method is proposed for calibrating the radius of a rotating coil sensor by relaxing the metrological constraints on alignment and field errors of the reference quadrupole. A coil radius calibration considering a roll-angle misalignment of the measurement bench, the magnet, and the motor-drive unit is analyzed. Then, the error arising from higher-order harmonic field imperfections in the reference quadrupole is assessed. The method is validated by numerical field computation for both the higher-order harmonic errors and the roll-angle misalignment. Finally, an experimental proof-of-principle demonstration is carried out in a calibration magnet with sextupole harmonic.

1. Introduction

In particle accelerators, magnetic measurements are necessary for establishing a suitable experimental coherence among machine requirements, beam physics simulations, and magnet development [2]. Beam physicists allocate a suitable budget for magnet misalignment and require experimental magnetic field maps pointing out the field errors (expressed as *multipoles* [3]). During magnet prototyping, measurements allow also design calculations, material properties, and fabrication methods to be verified [4]. Fields are measured also for monitoring the magnet behavior online; thus direct feedback to the accelerator control is provided for adjusting the beam bending and for tuning the acceleration parameters.

Based on these depicted findings, different measurements techniques are employed, based on various sensing elements, such as induction coils, oscillating wires, and Hall probes, among others [5,6]. The induction coil is based on the Faraday's law of induction, where the sensing element [7] is turned inside the magnet's aperture in order to provide a spatial harmonic description of the field (*harmonic coil* [3]). A coil consists of several rectangular loops of conducting wire, usually stretched during the winding on a rigid core and then glued to assure a well-defined and stable geometry. Coils can be manufactured by traditional winding methods or printed-circuit board (PCB) [8] technology. The latter is especially suited for small-aperture magnets [9].

Manufacturing errors leading to deviations from the ideal design exist in both the technologies. For the PCBs, a misalignment between layers of different radii is typical. Therefore, an accurate calibration is needed: Several physical parameters of the coil, such as rotation radius, coil area, phase angle, tilt, number of turns, and opening angle

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have to be measured carefully in order to reach the required metrological target.

The calibration based on a reference quadrupole magnet [1] is currently used in rotating coil systems. The magnetic-equivalent rotation radius can be obtained in a reference quadrupole field either by measuring the focusing strength, or rotating the coil by a given angle [1] or also before and after a translation in the horizontal (xz) and vertical (yz) planes.

The calibration assumes that the coil and the reference magnet axes are perfectly aligned, limiting the mathematical analysis to two dimensions. However, if significant roll and swing misalignment errors are present, this gives rise to significant calibration errors. Moreover, the equations used to calculate the radius is based on the *feed-down* effect from the quadrupole component [1], by assuming all the contributions of higher-order terms as negligible. This is justified because the dominant field component in the reference magnet is much larger than the field errors of higher-order multipoles [10]. However, if this assumption is not verified, a sextupole magnet is used as reference, or an in-situ calibration is carried out in a nonideal magnet, significant errors arise. Therefore, a reference magnet with stringent metrological constraints of harmonic field quality and alignment is required. This is difficult to achieve, however, for small-apertures or rare-earth permanent magnets.

In this paper, a method is analyzed for calibrating the rotation radius of coils using a reference quadrupole magnet with a higher-order harmonic error, or a misalignment with the coil axis. In particular, in Section 2, the presence of a roll-angle misalignment between the coil axis and the reference magnetic field axis, and higher-order harmonics of the reference quadrupole is analyzed. In Section 3, the effect of coil radius calibration in a quadrupole with a sextupole or octupole error component is simulated numerically by using the field computation program ROXIE [3]. In Section 4, experimental results for validating the proposed method are given.

2. Calibration method

In the following, the two cases of radius calibration are analyzed for rotating coils using a nonideal reference quadrupole having (i) *roll-angle misalignment*, or (ii) *higher-order harmonics*.

2.1. Radius calibration considering roll-angle misalignment

The rotating-coil radius is calibrated by means of two measurements, taken at two different positions of the coil inside a reference quadrupole magnet. The following hypotheses are assumed about the set up and the measurement method:

* The reference quadrupole magnet has a cylindrical symmetry along the longitudinal axis z defining the global reference frame $\{x, y, z\}$.
* The misalignment of the reference quadrupole is modeled as a rotation (roll) around the z axis, without any component of pitch and yaw. The effect on the calibration error of higher-multipole field errors in the reference magnet is neglected, an assumption that will be challenged in the next section.
* Possible misalignment errors among the reference magnet, the coil support, and the displacement stages remain constant between the two measurements. This is a reasonable assumption, owing to the solid structure of the support posts and tables.
* The angular encoder of the rotating coil system (rigidly mounted between the driving system and the coil) is ideal, except for a rotation uncertainty φ_e.
* Between the two measurements, the coil is supposed to be purely translated on the magnet section with respect to the global reference frame from an initial position in the complex plain $z = x + iy$ by $\Delta z = z_b - z_a$ ($|\Delta z| = d$), without loss of generality, the displacement of the harmonic coil is assumed to be confined to the horizontal plane of the reference magnet, hence Δz coincides with Δx. The distance d is known with an uncertainty of ± 0.01 mm.

Let us consider only a transverse section of the measurement setup in the global 2D reference frame $\{x, y\}$ and the frames shown in Fig. 1:

* *Gravity frame*: $\{x_h, y_h\}$, used as external reference, and ideally coincident with the global reference frame $\{x, y\}$;
* *Magnet frame*: $\{x_m, y_m\}$, misaligned by the angle φ_m with the magnet geometric frame which is (not shown in Fig. 1 for the sake of clarity) defined according to the physical dimensions of the magnet, and supposed here as coincident with the gravity frame;
* *Coil Frame*: $\{x_c, y_c\}$, related also to the coils polarity, (represented in Fig. 1 as $\{x_a, y_a\}$ and $\{x_b, y_b\}$ for the two measurements, centered at z_a and z_b, respectively), and misaligned by the angle φ_a with respect to the gravity frame $\{x_h, y_h\}$;
* *Shaft Frame*: $\{x_s, y_s\}$: related to the shaft which supports the coil assembly;
* *Encoder Frame*: $\{x_e, y_e\}$: related to the frame of the rotary encoder installed on the test-bench. This frame can be rotated in order to be aligned according to the horizontal plane by zeroing the encoder.
* *Stages Frame*: $\{x_t, y_t\}$ related to the linear stage used to displace the magnet with respect to the coil during the in-situ calibration. The misalignment φ_t (Fig. 1) between the linear stage frame and the gravity frame induces an error on the coil phase computed during the coil in-situ calibration.

According to the measurement method of the harmonic coils [3], the 2π periodic voltage signal, resulting from the coil rotation inside the reference magnetic field, is developed into a Fourier series. The multipole field errors correspond to the Fourier series coefficients of the radial component of the magnetic flux density on the reference/measurement radius. The measured raw data are the integrated voltage signals that correspond to the flux linkage in