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A reconfigurable miniaturized transducer based on rotating coils for testing particle accelerator magnets

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ABSTRACT

The design of a reconfigurable transducer, based on rotating coils realized by printed circuit board (PCB), is proposed for testing magnets in particle accelerators. Despite classical rotating coils, the sensitivity of this transducers is not completely established with the design. Different configurations allow to tune sensitivity to the specific components of the magnetic flux density to be measured. At this aim, specific field harmonics such as dipole, quadrupole, sextupole, octupole, and decapole can be suppressed. Thus, the same accuracy level can be ensured in measuring the field quality of several types of magnets.

In this paper, first, conventional design criteria are recalled. Then, the design of the reconfigurable transducer based on four coils to suppress undesired field harmonics, from dipole up to decapole, is illustrated. The possibility of using both radial and tangential geometry, without affecting compensation quality, is highlighted too. Finally, a metrological analysis about the transducer manufacturing is reported, proving that the uncertainty arising from the PCB production is made negligible.

1. Introduction

Magnetic measurements are crucial in the acceptance process of magnets for particle accelerators. A magnet can be installed only if its field quality complies with criteria established by accelerator designers [1–4]. In this respect, the magnetic flux density **B** is usefully described in terms of *field harmonics*, relying on a series expansion. The set of coefficients of this series are known as *multipole coefficients* [5]. Even though, in an ideal magnet, the field would be characterized solely by a specific flux distribution, in practice, non-idealities introduce field errors, modeled as unwanted multipoles in the series expansion of **B**. Such errors mainly arise from manufacturing and assembly and cannot be assessed easily through numerical simulations. In fact, simulations are widely used during the magnet design, but an experimental campaign is mandatory for the design validation. Therefore, the field multipoles must be measured both to validate the magnet design and to verify magnet acceptance criteria [1–5].

In literature, the techniques employed to measure the magnetic flux density of a magnet are mainly based on wires [6,7], Hall transducers [8–10], or sensing coils [11–13]. The choice of the measurement principle depends on the characteristics of the magnet under test and on the desired accuracy. For instance, rotating coils are considered as the most accurate reference for measuring field harmonics in particle accelerators [11,14]. These transducers received great attention from the scientific community also in other applications, such as fluxgates [15–19]. In particular, rotating coils can be employed to selectively filter out undesired field harmonics [13,20,21]. However, each coil assembly is to be designed, optimized, and manufactured specifically with a predefined configuration, in order to carry out a specific measurement task.

In the last decades, printed circuit boards (PCB) have been used in order to reduce size and costs of coil-based transducers [22–26]. Only recently, technological advances have allowed the manufacturing of PCB-based rotating coils with performance comparable to their classical counterpart [27]. Furthermore, PCBs could provide flexibility in configuring the coil transducer.

With this idea in mind, the present paper proposes a reconfigurable PCB-based rotating coil transducer. The sensitivity to field harmonics is adjustable so to selectively measure a desired multipole or to compensate specific harmonics. In particular, in Section 2, conventional rotating coil designs and compensation schemes are reviewed. Then, in Section 3, a reconfigurable design involving four coils to suppress harmonics from dipole up to decapole is illustrated. In the same section, the possibility of exploiting both radial and tangential geometry without affecting compensation quality is also highlighted. Finally, in Section 4, some metrological considerations about the PCB manufacturing are reported, together with an estimation of how production uncertainties influence the overall transducer sensitivity.

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2. Background

In this section, the theory behind the design of rotating coil sensors is briefly recalled. Let us consider a two-dimensional problem under the hypothesis of long and straight accelerator magnet. In practice, this 2D discussion will be valid far from the magnet edges, and when the magnet curvature is negligible compared to the coil dimensions. Let us also consider a cylindrical coordinate system (r, φ, z) with the axis z coinciding with the magnetic axis. The magnet aperture Ω_a is a two-dimensional domain where a reference system based on the polar coordinates (r, φ) is established. If the magnet aperture is free of currents and/or magnetized materials, the components of the magnetic flux density **B** are

$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} C_n(r_0) \sin\left(n\varphi - n\alpha_n(r_0)\right) \tag{1}$$

and

$$B_\varphi(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} C_n(r_0) \cos\left(n\varphi - n\alpha_n(r_0)\right), \tag{2}$$

where r_0 is a reference radius, and $C_n(r_0)$ and $\alpha_n(r_0)$ are extracted from a Fourier analysis of $B_r(r_0, \varphi)$ and $B_\varphi(r_0, \varphi)$. B_r and B_φ at the reference radius r_0 can be either measured or evaluated numerically [5,11]. The circle of radius r_0 has to belong to Ω_a. The terms of the series are called *field harmonics* or *multipoles*, while the coefficients are called *multipole coefficients*. The index n identifies the nth coefficient and corresponds to a specific flux density distribution. The "European convention" has been adopted for n [28]. The field **B** can also be described in Cartesian coordinates by introducing the complex variable $\mathbf{z} = x + jy = re^{j\varphi}$ [11]:

$$\mathbf{B}(\mathbf{z}) = B_y(x,y) + jB_x(x,y) = \sum_{n=1}^{\infty} C_n e^{-jn\alpha_n} \left(\frac{\mathbf{z}}{r_0}\right)^{n-1}, \tag{3}$$

where the dependence of C_n and α_n from r_0 is omitted to simplify the notation. Note that the complex variable **z** is not to be confused with the longitudinal coordinate z.

In a coil transducer, the magnetic flux density is measured indirectly by the voltage induced at the coil terminals, namely the time derivative of the magnetic flux Φ through the coil surface S

$$V(t) = -\frac{\partial\Phi(t)}{\partial t} = -\frac{\partial}{\partial t}\left(\iint_S \mathbf{B}\cdot\hat{\mathbf{n}}\, dS\right), \tag{4}$$

where $\hat{\mathbf{n}}$ is the unit vector normal to S, identifying the orientation of the coil surface itself. A non-zero voltage is measured only if the magnetic flux varies with time, and, to this aim, rotating coils can be employed. In this case, the rotation axis is chosen so that it coincides with the magnetic axis of the accelerator magnet (axis z).

In the following, Section 2.1 recapitulates the main conventional design of rotating coil transducers, while, Section 2.2 reviews existing compensation schemes.

2.1. Conventional rotating coil design

The magnetic flux Φ through a coil of arbitrary shape running parallel to the axis z can be written as [11]

$$\Phi = \mathrm{Re}\left\{\sum_{n=1}^{\infty} C_n e^{-jn\alpha_n} \frac{NLr_0}{n}\left[\left(\frac{\mathbf{z_2}}{r_0}\right)^n - \left(\frac{\mathbf{z_1}}{r_0}\right)^n\right]\right\}, \tag{5}$$

where L is the extension of the coil in the z-axis direction (longitudinal direction), N the number of coil turns, and $\mathbf{z_1}$ and $\mathbf{z_2}$ the intersection of the coil edges with the xy-plane (Fig. 1). If the coil is rotating with angular speed ω, $\mathbf{z_1} = \mathbf{z_{1,0}}e^{j\omega t}$ and $\mathbf{z_2} = \mathbf{z_{2,0}}e^{j\omega t}$ (where $\mathbf{z_{1,0}} = r_{1,0}e^{j\varphi_0}$ and $\mathbf{z_{2,0}} = r_{2,0}e^{j\varphi_0}$) identify the position of the coil at $t = 0$.

The *coil sensitivity factor* is defined as

$$K_n = \frac{NLr_0}{n}\left[\left(\frac{\mathbf{z_{2,0}}}{r_0}\right)^n - \left(\frac{\mathbf{z_{1,0}}}{r_0}\right)^n\right]. \tag{6}$$

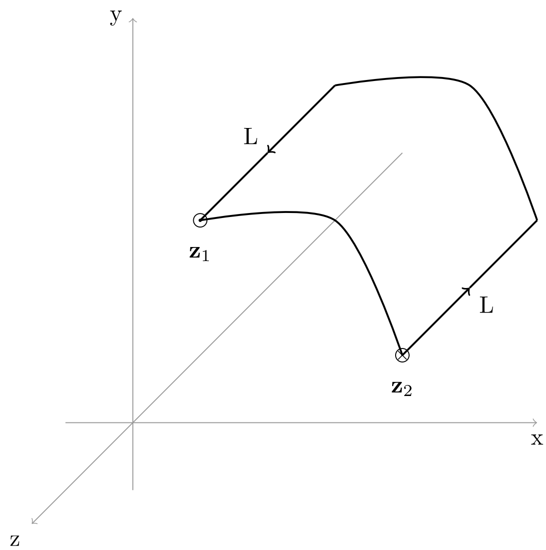

Fig. 1. A coil with longitudinal edges of length L parallel to the z-axis, intersecting the xy-plane in the points $\mathbf{z}_1 = x_1 + jy_1$ and $\mathbf{z}_2 = x_2 + jy_2$.

K_n quantifies the sensitivity of the coil to the nth field harmonic, and it depends on the coil geometry, while it is independent of ω.

The rectangular geometry of the coil loop is common in accelerator magnet applications, because it provides precise geometry and simplifies calculations [22]. Two main rotating coil types are usually considered, tangential and radial coils. A tangential coil has the linkage surface orthogonal to the rotating shaft radius: its longitudinal edges are at the same distance r_c from the rotation axis, and it has an aperture δ, as shown in Fig. 2a. The magnetic flux through a rotating tangential coil is

$$\Phi = \mathrm{Re}\left\{\sum_{n=1}^{\infty} C_n e^{jn(\omega t - \alpha_n)} \frac{-2jNLr_0}{n} e^{jn\varphi_0}\left(\frac{r_c}{r_0}\right)^n \sin\left(\frac{n\delta}{2}\right)\right\} \tag{7}$$

and the coil sensitivity factor is

$$K_n^{tan} = e^{j(n\varphi_0 - \frac{\pi}{2})}\frac{2NLr_0}{n}\left(\frac{r_c}{r_0}\right)^n \sin\left(\frac{n\delta}{2}\right). \tag{8}$$

Analogously, in a radial configuration (Fig. 2b), the coil is in a radial plane of the rotating shaft, so that $\mathbf{z_1} = r_1e^{j(\omega t + \varphi_0)}$ and $\mathbf{z_2} = r_2e^{j(\omega t + \varphi_0)}$. The flux linkage is

$$\Phi = \mathrm{Re}\left\{\sum_{n=1}^{\infty} C_n e^{jn(\omega t - \alpha_n)} \frac{NLr_0}{n} e^{jn\varphi_0}\left[\left(\frac{r_2}{r_0}\right)^n - \left(\frac{r_1}{r_0}\right)^n\right]\right\} \tag{9}$$

and the coil sensitivity factor is

$$K_n^{rad} = e^{jn\varphi_0}\frac{NLr_0}{n}\left[\left(\frac{r_2}{r_0}\right)^n - \left(\frac{r_1}{r_0}\right)^n\right]. \tag{10}$$

This factor depends on the coil geometry and on the index n differently from the tangential case. In the equations shown above, r_1 is negative when the rotation axis intersects the radial coil. This statement will become clearer with the example of the dipole coil in the following subsection.

2.1.1. Dipole and quadrupole coils

A *dipole coil* is shown in Fig. 3a. This is a particular radial coil (Fig. 2b) with $r_2 = r_c$ and $r_1 = -r_c$. The coil sensitivity factor is calculated by applying Eq. (10) with $\varphi_0 = 0$, corresponding to the coil on the x-axis at $t = 0$. It results

$$K_n^{dp} = \begin{cases} \dfrac{2NLr_0}{n}\left(\dfrac{r_c}{r_0}\right)^n & \text{for odd n} \\ 0 & \text{for even n} \end{cases} \tag{11}$$