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An Induction-Coil Measurement System for Normal- and Superconducting Solenoids

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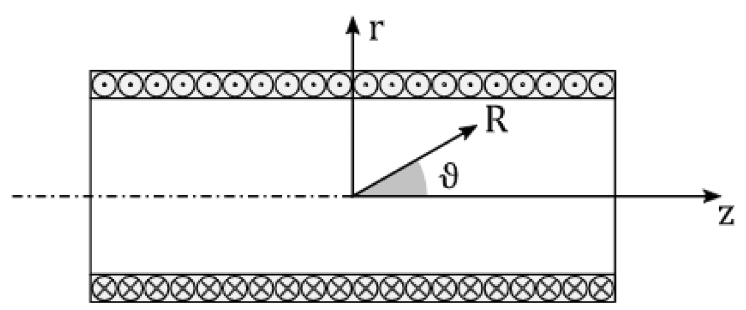
Abstract

The magnetic measurement of solenoids relies on different methods to characterize the field quality and locate the magnetic axis. Usually, Hall mappers and stretched-wire systems are used for these tasks. This paper presents an alternative flux metric method to measure the radial field dependence and the magnetic axis with a single instrument. The solenoidal-field transducer is based on a disc-shaped induction-coil array with concentric coils and 90 deg. arc segments mounted on a translation stage. This allows to sample the magnet along its axis and to extract both the longitudinal and transversal field components. We present the design, development, production challenges, and validation of the new instrument for which printed-circuit board technology has become a new standard.

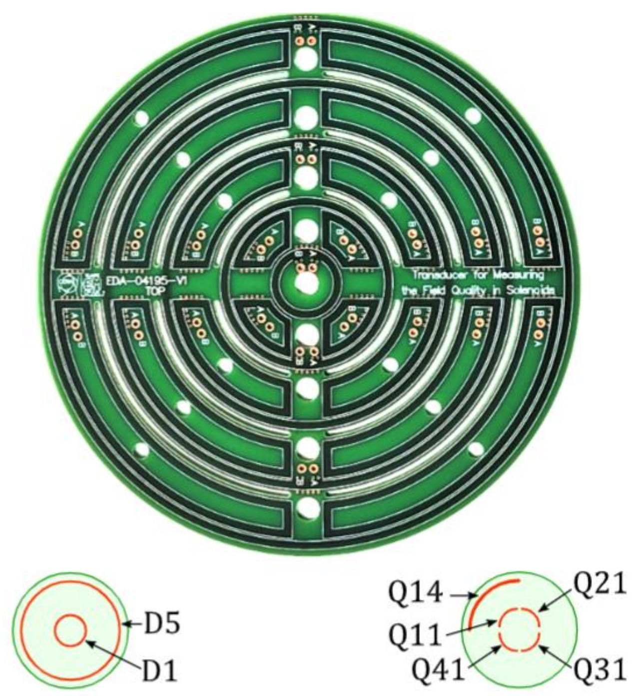
Measurement principle

Solving a boundary value problem in spherical coordinates (R,ϑ,φ) will provide us with a multipole expression for **solenoids** when assuming axial symmetry. From the magnetic scalar potential, we can calculate the components of the magnetic flux density. Using the Legendre series, we get:



$$B_z(R,\vartheta) = -\mu_0 \sum_{n=1}^{\infty} \mathcal{A}_n\, n\, R^{n-1}\, P_{n-1}(\cos\vartheta)\,,$$
$$B_r(R,\vartheta) = \mu_0 \sum_{n=1}^{\infty} \mathcal{A}_n\, R^{n-1}\, P^1_{n-1}(\cos\vartheta)\,.$$

The field transducer comprises two sets of **induction coils**. The first set of coils (D_i, $I \in [1,5]$) consists of five nested circular disks, while the second set consists of 4×4 arcs of 90 degrees opening angle ($Q_{q,j}$).



When the **measurement** system is translated along the bore, the induced voltages across the coils are acquired. Considering the longitudinal position z_c as a precisely known parameter, determined by the longitudinal displacement system of the sensor, the average flux density across the induction coils can be expanded up to 5th order as:

$$B_z(r) = p_0(z_c) + p_2(z_c)\, r^2 + p_4(z_c)\, r^4 + \ldots$$
$$B_r(r) = q_1(z_c)\, r + q_3(z_c)\, r^3 + q_5(z_c)\, r^5 + \ldots \qquad (2)$$

Measurement procedure

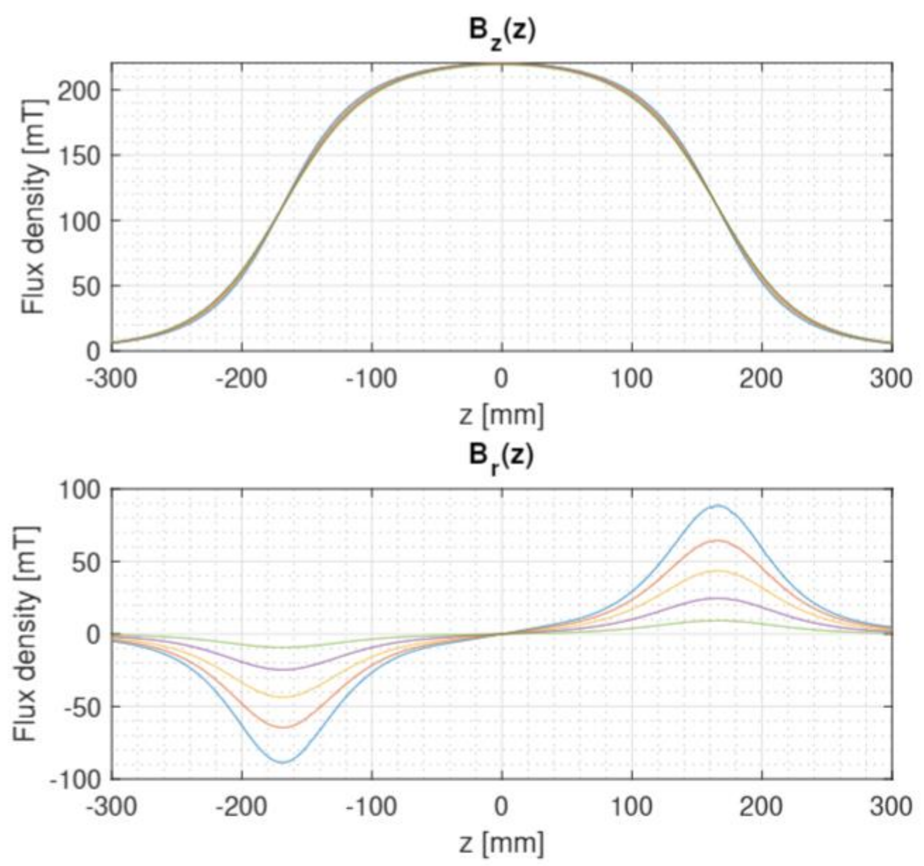
The average axial field through each circular disk is calculated integrating the induced voltages between trigger points from the linear encoder. The **radial dependence** of the **longitudinal** flux density can be deduced from the measurements by subtracting the flux linkages of two concentric disks:

$$\bar{B}_{z,i}(z_k) = \frac{\phi_i(z_k) - \phi_{i-1}(z_k)}{S_i - S_{i-1}}. \qquad (3)$$

For measuring the absolute field strength at a position z_k, the induction coils must be moved from the zero-field region outside of the magnet. **The radial field component** is deduced from the rate of change of flux divided by the cylinder surface traced by each disk edge during the longitudinal displacement:

$$\bar{B}_{r,i}(z_k) = \frac{\phi_i(z_k) - \phi_i(z_{k-1})}{2\pi r_i\,(z_k - z_{k-1})N}, \qquad (4)$$

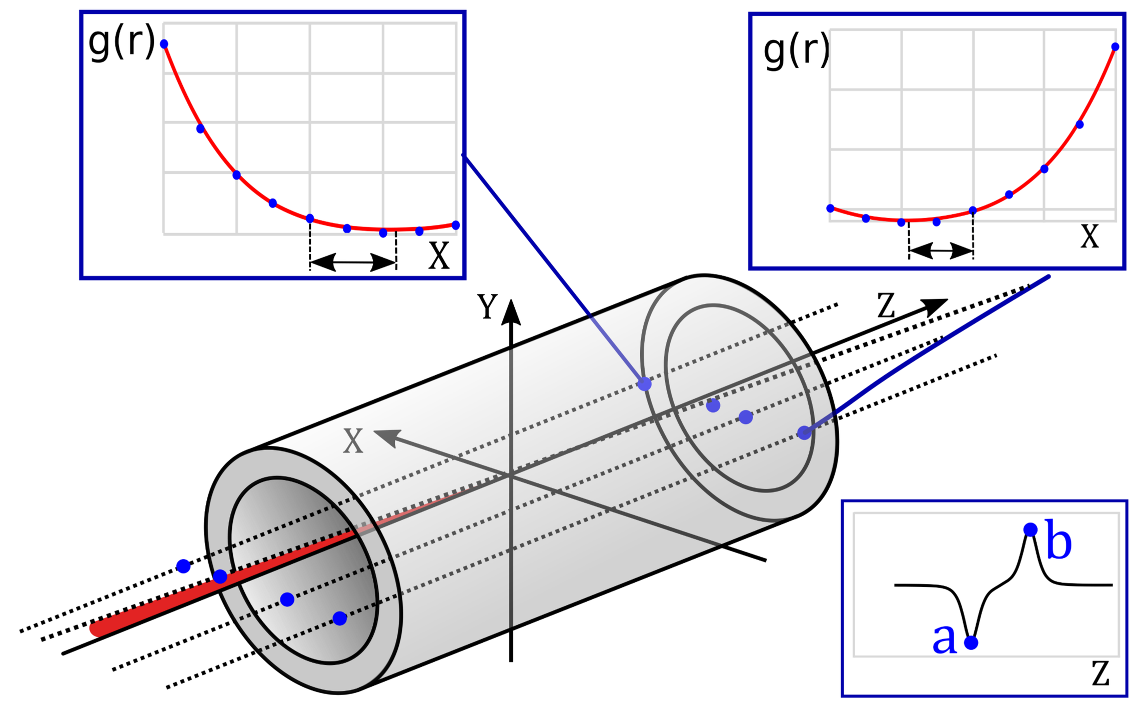
where N is the number of coil turns, and (z_k–z_{k-1}) is the longitudinal displacement step.



The **quarter-arc** coils $Q_{q,j}$ of the sensor can be employed to locate the magnetic axis of the solenoid with respect to the mechanical center of the field sensor. At every trigger point z_k, 9 signals for each axis (x and y) are acquired. Consider now that the measured quantities are the local gradients of B_z averaged over the surfaces of the quarter arcs: g(**r**):=grad_r **B**·e_z. These signals are then fitted with the expression in Eq. 1.

Measurement results

To validate the proposed method for the axis location, measurements were taken along nine tracks, shifted on the horizontal plane in parallel to the geometric axis. The positions were precisely measured with the laser tracker. For every track, the measurements were averaged over 6 travel repetitions. The magnetic axis is found where the local field gradient takes its minimum. At each position z_k, Eq. 1 is used to fit the local field gradients. For this root-finding problem it is beneficial to consider the longitudinal points where the signal-to-noise ratio is maximal. This is the case at the **extremities** of the solenoid (positions a and b). Each measurement is fitted in its local reference frame and then transformed into the magnet frame. The results show that with a single track the magnetic axis can be located with a precision of 0.1 mm. When all tracks are fitted, the axis location is within 50 µm. Introducing a swing angle of the sensor, results have shown a precision within 0.1 mrad in identifying this swing angle.



Conclusions

The proposed method allows us to measure the field profiles of the B_z and B_r components with an accuracy of 10^{-5} with respect to the main field. The local field gradients were determined by moving the sensor along displaced tracks. This allowed the magnetic axis location with a precision of 0.1 (single track) and 0.05 mm (9 tracks), and 0.1 mrad for the swing angle. Proven the feasibility, a more accurate result may be expected by producing an optimized sensor for each particular project.