INVERSE PROBLEM-BASED MAGNETIC CHARACTERIZATION OF WEAKLY MAGNETIC ALLOYS

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Abstract

Understanding the magnetic properties of materials used in accelerator components is becoming increasingly important. For example, in the upcoming LHC upgrade at CERN, higher luminosity will boost the radiation dose received by the accelerator magnet's coil and consequently decrease its lifespan. Hence, a radiation shield with relative permeability less than 1.005 is required for some of the magnets closest to the detectors. The goal of this research is the design and validation of a new method for characterizing weakly magnetic materials, suitable to be used in quality control of series production. The proposed method is based on inverse analysis approach coupled with a finite-element model. A material with unknown permeability is inserted in the air gap of a dipole magnet and the consequent perturbations of the dipole background flux density are measured. The relative magnetic permeability is then identified through gray-box inverse modeling, based on a finite-element approach.

INTRODUCTION

High Luminosity-Large Hadron Collider (HL-LHC) is a project which aims to upgrade the Large Hadron Collider (LHC) in order to maintain scientific progress and exploit its full capacity. Increasing its peak luminosity by a factor of five over nominal value, a higher level of integrated luminosity will be achieved, nearly ten times the initial LHC design target [1].

This will cause an increment of the radiation dose inside the accelerator. The magnets most affected by this higher level of radiation are the LHC Warm Bending Magnets (MBW) and Warm Quadrupole Magnets (MQW) [2].

Protection of these normal conducting magnets in the LHC aims to reduce the radiation dose received by the magnet's coils and increase their lifespan. This will be done by specially manufactured Tungsten Heavy Alloy (WHA) pieces [3].

The selected commercial material, INERMET® IT180 [4] contains 5% of nickel and copper in unspecified proportions and it is marketed as non-magnetic. However, according to the available literature, its magnetic properties depend critically on the precise composition. Even if slightly paramagnetic, An eventual residual magnetization of this material could interfere with the magnetic field generated by the magnets and decrease the whole accelerator performance. Therefore, magnetic testing of the actual delivered pieces will be necessary. In particular, CERN has requested that the tungsten alloy used as radiation shield shows a relative magnetic permeability, μ_r, lower than 1.005.

In the literature, the most applied methods to characterize weak magnetic materials are: Vibrating sample magnetometer (VSM) [5], alternating gradient force magnetometer (AGFM) [6], classical fluxmetric approaches and force methods, such as the Faraday balance or the Gouy technique [7]. Although VSM and AGFM techniques are the most sensitive, their use is limited to specialized laboratories and they are not practical from an industrial point of view (series production) due to high costs and tight constraints on the specimen shape and volume. Force methods can display better sensitivity than the fluxmetric methods, but they are rather cumbersome and time-consuming. Fluxmetric methods, such as the CERN split-coil permeameter [8], have poor accuracy when the permeability is close to unit, mainly due to the extremely low SNR of the signal picked up by the sensing coil.

Instruments based on other methods, e.g. inductive such as the Foerster Magnetoscop [[9]], are also available commercially. The vast majority of these, however, are adapted for earth sciences applications or present other practical constraints limiting their use in an industrial context. In recent years several authors have focused their attention on inverse algorithms for the identification of the magnetic material characteristics [10], [11], [12] and [13]. However, these deal with characterization of ferromagnetic materials, whereas the feasibility of inverse problem formulation for the characterization of weakly magnetic materials has not been investigated thus far.

The goal of this research activity is the implementation and validation of a new perturbation-based method for the open circuit magnetic characterization of low-permeability magnetic materials by means of an inverse problem formulation. As proof of principle and to assess the proposed method's accuracy, this approach will be applied to a reference alloy sample with a known relative magnetic permeability [9].

MEASUREMENT SETUP

The layout of the open circuit measurement system, hosted at CERN's magnetic measurement laboratory in Geneva, is shown in Fig. 1. It mainly consists of (i) a reference dipole

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magnet (MCB22) able to generate a magnetic field up to 1 Tesla with uniformity better than $3 \cdot 10^{-4}$ over a volume of 1500 x 300 x 70 mm^3; (ii) a nuclear magnetic resonance teslameter (NMR - Metrolab PT2025) [15], sensitive to the norm of the vector flux density, with a precision of 0.1 parts per million (ppm) and an absolute accuracy of 5 ppm; and (iii) a high-precision linear translation stage and a stage controller for moving the NMR with a relative accuracy of 1 ppm and recording the relative distance between two consecutive measurements. The overall measurement system is automatized by means of a suite of interactive programs developed in C++ using a customized framework for magnetic measurements (PC FFMM) [[14]].

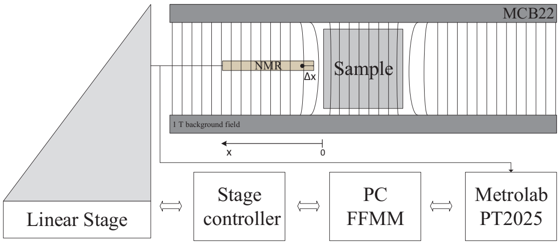

Figure 1: Measurement system layout.

INVERSE PROBLEM FORMULATION

The main idea of the proposed method consists of determining the relative magnetic permeability of the material under test by means of an inverse problem formulation [16] and 2D finite element simulations. The schematic diagram of the measurement principle is shown in Fig. 2.

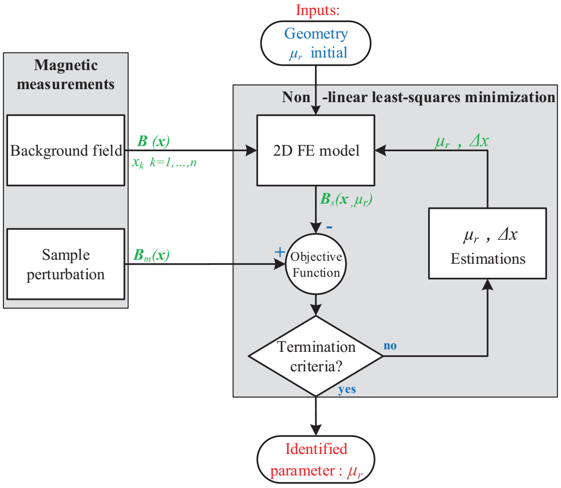

Figure 2: Flow chart of the proposed method.

Magnetic Measurements

An essential part of the proposed method is to detect the perturbation of the background field due to the presence of the sample under test in the dipole magnet by means of local magnetic measurements.

1. **Sample-induced perturbation measurements**: A cylindrical sample is placed in the uniform field region of the reference dipole and the magnetic flux densities, $B_m(x_k)$, at different distances from the sample are measured with the NMR sensor. The coordinates, x_k with $k = 1, ..., K$, are measured and recorded. In this case, the problem is axysimmetric and the x axis could in principle coincide with any radius. Both the sample and the sensor are positioned symmetrically with respect to the mid plane of the magnet gap.

2. **Background field measurements**: The same measurements are performed in the absence of the sample, under the same magnet excitation conditions.

Non Linear Least-squares Minimization

In general, inverse problems are essentially defined as the identification problem of unknown parameters from indirect measurements. The values of the unknown model parameters are recovered by iteratively minimizing the residual between the computer forward model responses and the physical measurements.
In this application, the unknown parameter is the relative permeability of the sample under test; the physical measurements are the values of the flux density $B_m(\mathbf{x})$ measured by the NMR teslameter; and the computer forward model responses are the flux density $B_s(\mathbf{x}, \mu_r)$ provided by a 2D FE model of the open circuit measurement system.

Finite Element Modeling The numerical model of the open circuit measurement system is constructed using a 2-D finite element method in FEMM [17], using Lua as scripting language [18]. The following assumptions have been made: i) the geometry is locally 2D; ii) the permeability in the sample is uniform and iii) inserting the sample inside the magnet does not affect appreciably its total reluctance (or, in other words, the boundary conditions for the FE model correspond to a uniform field with and without the sample).

Objective Functions We have considered an objective function OF representing the quadratic error between the measured and simulated quantities:

$$[\mu_r^*, \Delta x^*] = \arg \min_{\mu_r, \Delta x} OF(\mu_r, \Delta x, \mathbf{x}) \qquad (1)$$

where μ_r^* is the estimated relative magnetic permeability of the material and Δx the estimation of the distance sample-sensor offset. The first formulation, $C1$, is simply the quadratic sum of the relative differences between measured and simulated field. To improve accuracy a least squares approach has also been applied to the model, making the assumption that all variables are contaminated by noise, see Fig. 3. The main sources of uncertainty are (i) conformity to the model assumptions ϵ_g; (ii) the flux density measurements ϵ_B and the position measurements, characterized by two contribution, a systematic $\epsilon_{\Delta x}$ and an random ϵ_x.

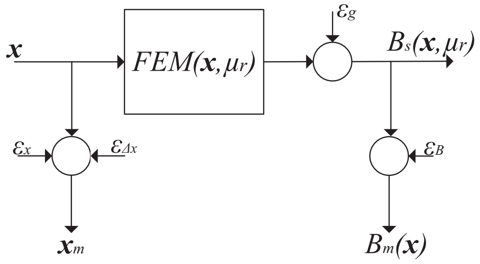

Figure 3: Diagram of the errors-in-variable approach

If the reasonable assumptions, $C2$, $\epsilon_g >> \epsilon_B$ and $\epsilon_{\Delta x} >> \epsilon_x$ are made, the objective function, can be written as follows:

$$OF(\mu_r, \Delta x, \mathbf{x}) = \sum_{k=1}^{K} \left(\frac{B_s(x_k + \Delta x, \mu_r) - B_m(x_k)}{B_m(x_k)} \right)^2 \qquad (2)$$

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RESULTS AND DISCUSSION

The results of the magnetic material identification based on the proposed inverse approach are presented and discussed in the following sections.

Magnetic Measurements

Figure 4 shows the results of the local magnetic measurements. In particular, the flux density generated from the dipole magnet in the case of perturbation due to the presence of the reference sample SN643 and in absence of sample (measurement of the background field), are presented. The perturbation decays asymptotically as the inverse of the distance cubed, as expected for the far field of an elementary magnetic dipole perturbation.

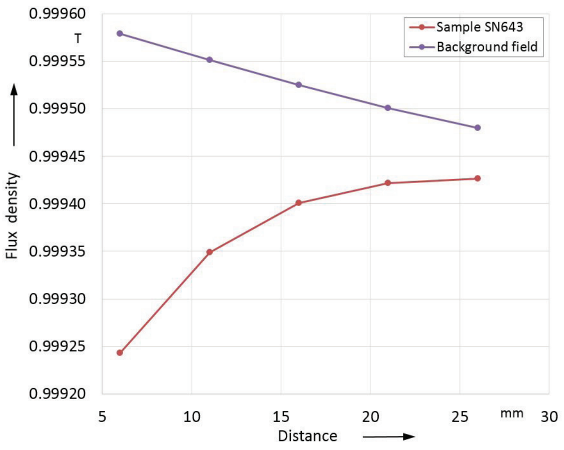

Figure 4: Magnetic measurements results

Relative Magnetic Permeability Identification

The results of the inverse problem formulation are summarized in Table 1. A good correspondence between the estimated and reference permeability is observed: both estimated values lie in the uncertainty range of the reference value. The smallest error is given unsurprisingly by the case 2, which includes an additional parameter into the fit. $C2$ tries to recover the distances sample-sensor at which the local magnetic measurements are performed assuming that all the distances are affected by the same offset. This is consistent with the fact that the actual position of the probe inside the sensor is known with an uncertainty of 1 mm, while the relative distance between two measurements is known with an uncertainty of 10^{-3} mm. Further work with different reference samples is required in order to assess whether this formulation is well-posed or not.

Table 1: Magnetic Relative Permeability Identification - OF2

	Reference μ_r [-]	**Estimation** μ_r	Δx
$C1$	1.00384 ± 0.00031	1.00396	-
$C2$	1.00384 ± 0.00031	1.00392	-0.017

CONCLUSION

In this paper we proposed a method to identify the relative magnetic permeability of weakly magnetic materials immersed in a uniform, strong magnetic field. The proposed method solves an inverse problem starting from well-defined local magnetic measurements, followed by a numerical procedure, that is based on the finite element method. The method is general and could be used with different sample geometries (cube, bar, sphere, etc.) provided that appropriate 2D or 3D FE modeling is used. The case study shows good agreement between the estimated relative magnetic permeability and the reference value of the sample: the accuracy of the proposed method is better than 3% with respect to the susceptibility. This method, still while time-consuming at this stage, has been found to be effective for the difficult problem posed by weakly magnetic materials. In view of future series test campaigns, its efficiency could be improved by standardizing the setup and the shape of the sample.

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