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Identification of an arbitrary-surface harmonic magnetic model from close measurements

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Abstract—Decreasing spherical harmonic functions are widely used to identify and extrapolate the magnetic field produced by various devices. These functions are equivalent to a multipolar decomposition which orders the field according to its spatial decreasing rate. However this representation is not valid inside the Brillouin sphere, the smallest sphere enclosing the device. We introduce here the use of an alternative representation to replace the spherical harmonic functions when the measurement are inside the Brillouin sphere. This representation uses a basis of equivalent charges on a surface to reproduce the multipolar decomposition while being valid inside the Brillouin sphere. We demonstrate here the ability of this model to identify and extrapolate the field from very close measurements.

Index Terms—Inverse problem, multipolar decomposition, single-layer potential

I. INTRODUCTION

For various applications (including electromagnetic compatibility [1], human exposure [2], ship silencing [3]), the magnetic field produced by a device must be determined all around it. Interpolation on a measured grid and direct numerical modelling of the sources are not always possible and other alternatives must be found. Identification of a compact model from close magnetic measurements is a common approach.

Classically, the external field is represented by a multipolar expansion using the decreasing spherical harmonic functions. Each multipole (e.g., dipole, quadrupole) is associated to a spatial harmonic which presents a specific spatial decreasing law (e.g., $1/r^3$, $1/r^4$, with r the distance to the multipole). Nevertheless, this representation is only valid outside the Brillouin Sphere [4], the smallest sphere that encloses all the sources, and cannot be used in the close vicinity of the device.

In this paper, we propose to use a new multipolar representation that is valid in the close vicinity of the source to identify and extrapolate the field produced by this source. This original approach allows to put sensors closer to source, maximizing the signal to noise ratio.

II. MULTIPOLAR MODEL OF EQUIVALENT SOURCES

Any source can be represented on an enclosing surface S by equivalent charges (or single-layer potential) σ that produce the same field as the source outside this surface. The surface S can be chosen as close to the source as desired. The magnetic field \mathbf{H} can then be computed at any point P outside the surface S [5]:

$$\mathbf{H}(P) = -\nabla \int_{M \in S} \frac{\sigma(M)}{4\pi \|PM\|} dS \quad (1)$$

This single-layer potential can be decomposed into a multipolar basis $\{\sigma_{km}\}$ [6]:

$$\sigma = \sum_{k=1}^{\infty} \sum_{m=-k}^k c_{km} \sigma_{km} \quad (2)$$

with c_{km} the harmonic coefficients that depend only on the source and σ_{km} the vectors of the basis $\{\sigma_{km}\}$ that depend only on the choice of the surface S and need to be precomputed like defined in [6] (see Fig. 1). In a practical case, the infinite sum is truncated to a given order K .

This representation is still valid inside the Brillouin sphere while being multipolar in a weak sense i.e. a vector σ_{km} produces a field that decreases at least as fast as a multipole of order k outside the Brillouin sphere. Our goal is now to determine the coefficients c_{km} from a set of magnetic measurements.

III. IDENTIFICATION IN A BAYESIAN CONTEXT

If the number of magnetic sensors is limited or their location is constrained, the Bayesian context allows to add some prior information to help the identification. If we assume all the distributions as Gaussian, we can compute the maximum of the posterior distribution c_{MAP} [7]:

$$c_{\text{MAP}} = (A^t S_m^{-1} A + S_0^{-1})^{-1} (A^t S_m^{-1} b + S_0^{-1} c_0) \quad (3)$$

with A the direct influence matrix (the numerical integration of (1) for each vector of the harmonic basis), b the field

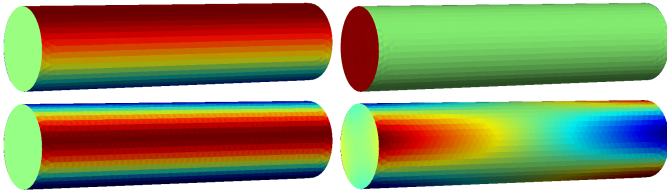


Fig. 1. Representation of vectors from the basis $\{\sigma_{km}\}$ on a cylinder. With from left to right and top to bottom: $k = 1$ and $m = 0$, $k = 1$ and $m = 1$, $k = 2$ and $m = -1$, $k = 3$ and $m = -2$.

measurements, c_0 and S_0 the mean and covariance matrix of the prior distribution and S_m the covariance matrix of the sampling distribution (associated to the measurement and model noise in our application).

IV. APPLICATION

We consider a magnetized open hollow steel cylinder. It is equipped with two lines of sensors (lines 1 and 2) for the identification. One sensor moves along a straight line under the cylinder (line 3), the measurements on this line are then compared to the extrapolation of the field (see Fig. 2). The cylinder has a diameter of 12 cm and a length of 50 cm. Lines 1 and 2 are 8 mm from the surface of the cylinder and hold 14 sensors which measure the longitudinal and orthoradial component of the field. Line 3 is 8 cm from the surface of the cylinder and 99 triaxial measurements were taken over the span of 3.4 m.

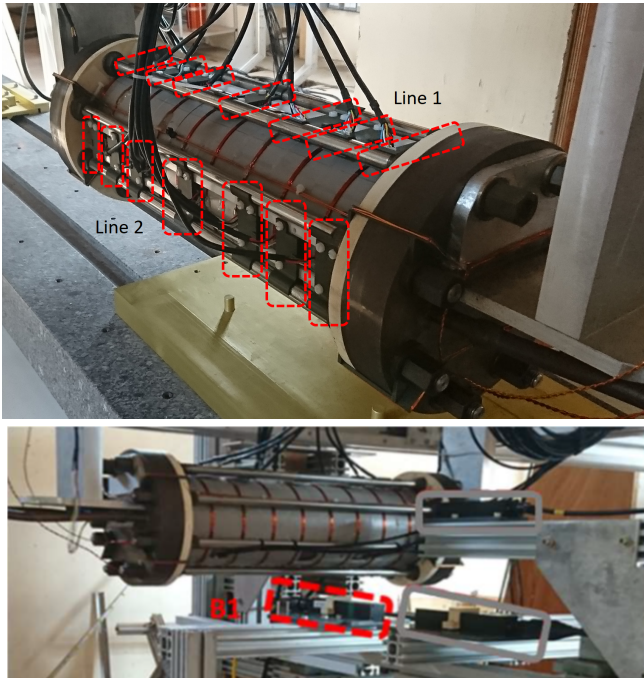


Fig. 2. Above: hollow cylinder and identification sensors on line 1 and 2, below: line 3 is obtained by moving the sensor B1 along the longitudinal axis.

The basis is constructed on a closed cylinder of same dimensions, this cylinder is meshed with 2104 triangles. As

the sensors are very close to the source we identify the harmonic coefficients c_{km} up to the 15th (i.e. $K(K+2) = 255$ coefficients to identify). As it is specific to the application we will give details on the choice of a physical prior in the full paper. The main idea is to determine the prior (c_0 and S_0) from several evaluation of a forward modeling of the physical problem by varying uncertain parameters. The number of forward computations is limited due to the implementation of the unscented transform [8]. We extrapolate the field produced by the cylinder on line 3 with the identified coefficients given by (3). We achieve an accurate extrapolation with less than 6% difference on every components of the magnetic field (see Fig. 3 for longitudinal component) demonstrating the good performance of this new representation in the case of very close measurements.

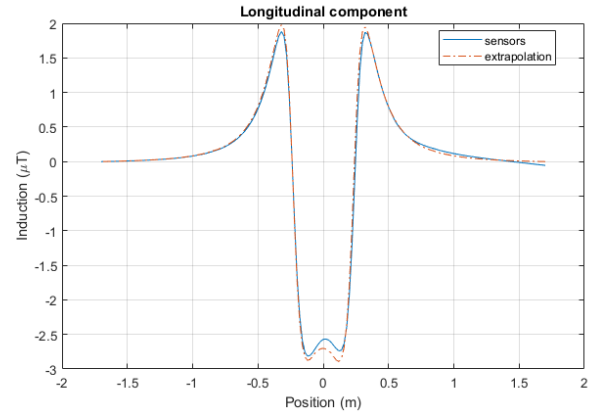


Fig. 3. Longitudinal component of the field produced by the cylinder on line 3 sensor, comparison between the measurements and the extrapolation.

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