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A New Inverse Integral Formulation for Thin Regions Magnetization Identification

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Abstract. This article focuses on the resolution of a magnetostatic inverse problem. The goal is to determine the permanent magnetization of a magnetic sheet from magnetic sensor measurements placed in the surrounded air region. An integral inverse formulation based on the face interpolation of the flux density is proposed, leading to robust determination of the coercive field with only few measurements data. The method can be used to study the magnetization change of a cylinder placed in a homogenous inductor field and under the effect of a mechanical strain.

Keywords: Thin magnetic region, inverse integral formulation, coercive field determination.

INTRODUCTION

The existence of magnetic mines requires ship's magnetic silencing. Identification of the hull magnetization is the key point of this process. The magnetic anomaly is directly linked to the magnetization that may be drastically modified by magnetoelasticity effects due to combination of pressure on hull and earth's magnetic field. Thus it is essential for the ship to evaluate its magnetic signature. To reach it, an inverse problem has to be solved in order to identify the magnetization from magnetic measurements. Previous work has shown a way to find the global magnetization by determining remanent magnetization [1]. In this paper, a new and more robust inverse approach is presented.

I. MAGNETOSTATIC FORWARD PROBLEM

Let us consider a ferromagnetic thin region Ω with a relative linear reluctivity ν and a coercive field \mathbf{H}_c placed in an inductor magnetic field \mathbf{H}_0 . This problem is governed by the following integral equation [2]:

$$\nu \mathbf{B} + \int_{\Omega} (\nu_0 - \nu) \mathbf{B} \cdot \nabla G = \mathbf{H}_0 + \mathbf{H}_c \quad (1)$$

where G is the Green's function. For magnetic sheets, the approximation of thin element simplifies a volume problem to a surface one by considering that the magnetic induction in the active region is uniform according to the thickness and is tangential to the sheet. In [2], it is shown that \mathbf{B} can be interpolated with face shape functions and expressed by a linear combination of magnetic flux Φ_B which flows through the equivalent faces (i.e the edge of the mesh for a surface region). In order to ensure the solenoidality of the flux into the mesh, the resolution is performed in the basis of independent fluxes Φ_{IB} [2]. Applying a Galerkin method, a linear system is obtained:

$$M \Phi_{BI} = S_{H_0} + S_{H_c} \quad (2)$$

where N_{BI} is the number of independent fluxes, $M \in \mathbb{R}^{N_{BI} \times N_{BI}}$, $\Phi_{BI} \in \mathbb{R}^{N_{BI} \times 1}$, $S_{H_0} \in \mathbb{R}^{N_{BI} \times 1}$ and $S_{H_c} \in \mathbb{R}^{N_{BI} \times 1}$. In a forward problem, coercive and inductor fields are known. However, in the context of an inverse problem, \mathbf{H}_c (which is an image of the local permanent magnetization) is unknown. Measurements have to be added.

II. INVERSE PROBLEM FORMULATION

The magnetic field in air can be expressed with the following integral expression:

$$\mathbf{H}_{air} = \int_{\Omega} (\nu_0 - \nu) \mathbf{B} \cdot \nabla G - \mathbf{H}_0 \quad (3)$$

Besides, assume that some magnetic sensors are placed in the surrounding air region. Equation (3) can be discretized leading to the following matrix system:

$$B_{mes} = A \Phi_{BI} \quad (4)$$

where N_{bmes} is the number of measurements, $B_{mes} \in \mathbb{R}^{N_{bmes} \times 1}$ and $A \in \mathbb{R}^{N_{bmes} \times N_{BI}}$.

In context of inverse problems, \mathbf{H}_C has to be considered as an unknown of the problem. To determine it, an interpolated function space has to be chosen. A good choice is also the face shape functions. The last term in (2) can be replaced by a matrix product keeping unknowns associated to \mathbf{H}_C explicit and leading to a new matrix system:

$$M\Phi_{BI} - N\Phi_{Hc} = S_{H0} \quad (5)$$

By combining (4) and (5), the final matrix system to solve is given by:

$$-A M^{-1} N \Phi_{Hc} = B_{mes} - A M^{-1} S_{H0} \quad (6)$$

To solve (6) in order to get the unknowns Φ_{Hc} , a balanced singular values decomposition (SVD) is used to improve the condition number of the final matrix system. Let us notice that the solution of the problem is not unique and the use of the SVD leads to the solution with the minimal norm. To physically minimize \mathbf{H}_C fluxes flowing through the shell does not make sense. It is more efficient to prioritize a solution which ensures the regularity of the flux. This is why it is preferable to replace the problem's unknowns by a fictive scalar distribution which is the surface divergence of \mathbf{H}_c . This solution leads to a regular and physical distribution.

III. RESULTS

An experiment (figure 1) has been set up with a cylinder which is filled by oil and can be pressurized thanks to a pump. Placed in a given homogenous magnetic field and due to the magneto-elastic effect, the magnetization and therefore the coercive field are modified [3]. Eight tri-axes fluxgate magnetic sensors are placed around the device for the inversion.

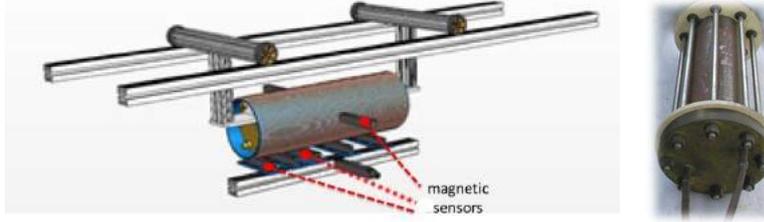


Figure 1: Plans of the experimental set up (left), pressurized cylinder (right).

The device is magnetized under the combination of an axial uniform magnetic field of $40 \mu\text{T}$ and an applied internal pressure of 10 MPa . \mathbf{H}_C is determined (figure 2). In order to check if the state of the shell has correctly been identified, the magnetic field is then computed on a line and compared with others measurements. Both curves match, the error being less than 1%. It demonstrates the efficiency of the method. In the full paper, the advantages of this identification method compared to [1] will be discussed.

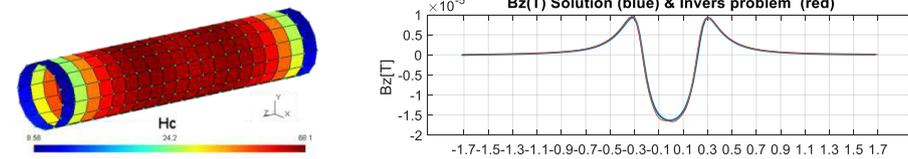


Figure 2: Distribution of magnetic coercive field on the cylinder (A/m) (left), longitudinal magnetic induction on a line under the device (blue predicted / red measured) (right).

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