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# Identification of ferromagnetic thin sheets magnetization

## Use of gradient and potential measurements

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### Abstract

**Purpose** – This paper aims to present the use of magnetic gradient, and magnetic potential measurements in the specific case of magnetization identification for a thin sheet. Usually, induction measurements are only used.

**Design/methodology/approach** – After a brief description of the magnetic gradient and magnetic scalar potential notions, methods to calculate them are presented and validated. These two kinds of measurements are tested for a numerical identification case. Then, virtual measurements can be generated and used for inverse problem resolution. Advantages of using induction, magnetic gradient or magnetic potential measurements are then discussed.

**Findings** – A previous method to solve inverse problem based on induction measurement has been increased by the capability of using other kind of measurements. A numerical approach has allowed to validate the use of magnetic gradient or magnetic scalar potential measurement as information sources.

**Originality/value** – Usually, induction measurements are only used. Inversion resolution using other kind of measurements than the induction can be made. An experimental validation has been done for gradient measurements.

**Keywords** Magnetism, Ships, Ferroelectricity, Measurement

**Paper type** Research paper

### 1. Introduction

The Laboratory for Ships Magnetism is in charge of studying the vulnerability of Navy vessels and equipments and the possibilities of reducing their magnetic signatures.

Since, 2007, its activity is grouped in a dedicated team for low magnetic field study activity in the Electrical Engineering Laboratory of Grenoble (G2ELab/ERT CMF).

In this paper, we focus on the signature created by ships' ferromagnetic hull. This magnetic anomaly is a function of an induced magnetization, created by earth field, and a permanent one, which depends on the magnetic history of the material. Because we have not any knowledge about this history, magnetic measurements around the sheet are necessary to evaluate the total magnetization.

The classical approach is provided thanks to induction measurements (fluxgate sensors). These sensors are placed inside the hull, and then, thanks to the resolution of an inverse problem, a magnetization distribution, located on the hull, is get. Thus, it is possible to predict the magnetic field outside and then to reduce it by adjusting currents in degaussing loops 0 (Figure 1).

However, induction measurements are not the only measurements which can be used. This paper proposes to solve the inverse problem with two new kinds of values (measurements): magnetic gradient and magnetic potential. The work presented

is a numerical study. Both kinds of measurement inversions are tested and their reliability to predict the field outside the ship are presented.

## 2. Direct problem formulation

Considering the magnetic induction vector  $\mathbf{B}(\mathbf{P})$ , we can define the magnetic gradient as equation (1):

$$\mathbf{G}(\mathbf{P}) = \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} \quad (1)$$

For magnetic steady state problem, without source, we obtain two important properties of the gradient (equation (2)):

$$\text{Tr}(\mathbf{G}(\mathbf{P})) = 0 \quad \text{and} \quad \mathbf{G}(\mathbf{P})^T = \mathbf{G}(\mathbf{P}) \quad (2)$$

with:  $\text{Tr}(\mathbf{A})$  the trace of the matrix  $\mathbf{A}$ .

The magnetic gradient can be defined considering partial derivative of the magnetic induction (equation (3)):

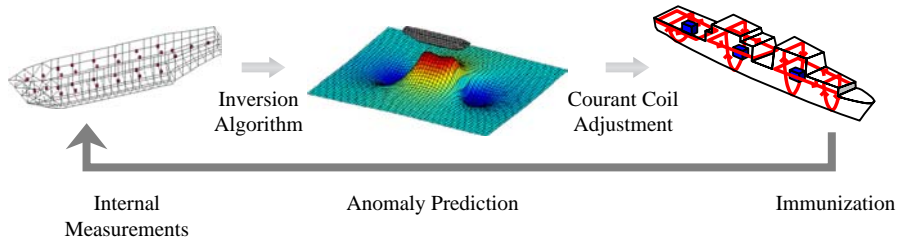
$$G(M) = \left[ \frac{\partial \vec{B}}{\partial x} \quad \frac{\partial \vec{B}}{\partial y} \quad \frac{\partial \vec{B}}{\partial z} \right] \quad (3)$$

Let us consider the surface  $S$ , meshed into  $n$  elements  $S_i$  delimited by a lines  $L_i$ , with a thickness  $e$  and an external normal  $\mathbf{n}_i$  tangential to  $S$  (Figure 2).

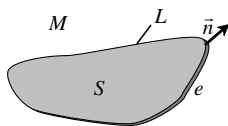
The magnetic induction at point  $M$  is defined by the equation (4):

$$\vec{\mathbf{B}}(M) = \mu_0(\vec{\mathbf{H}}_0 + \vec{\mathbf{H}}_{\text{red}}) \quad (4)$$

with:  $\vec{\mathbf{H}}_0$ , field created by magnetic sources and  $\vec{\mathbf{H}}_{\text{red}}$ , field created by the object.



**Figure 1.**  
Closed loop degaussing  
system principle



**Figure 2.**  
Surface magnetic object

Each element  $S_i$  has a uniform magnetization  $M_i$ . The induction created by  $S$  on a sensor placed at a point  $P$  located in the air region is:

$$B_{\text{mes}}(P) = -\frac{\mu_0 e}{4\pi} \sum_i^n \int_L M_i \cdot n_i \frac{r}{r^3} dL \quad (5)$$

where:  $r$  is the distance between the sensor and the integration point. This expression is an integral one and directly links the hull's magnetization to the induction measurements. This expression is then easy to inverse.

The expression of the magnetic gradient at the same point  $P$  is:

$$\frac{\partial B_{\text{mes}}}{\partial x}(P) = -\frac{\mu_0 e}{4\pi} \sum_i^n \int_L M_i \cdot n_i \left( \frac{-3r \cdot u_x}{r^5} r + \frac{u_x}{r^3} \right) dL_i \quad (6)$$

Same expressions can be provided for the other components.

With the same approach, the expression of the magnetic potential at  $P$  is:

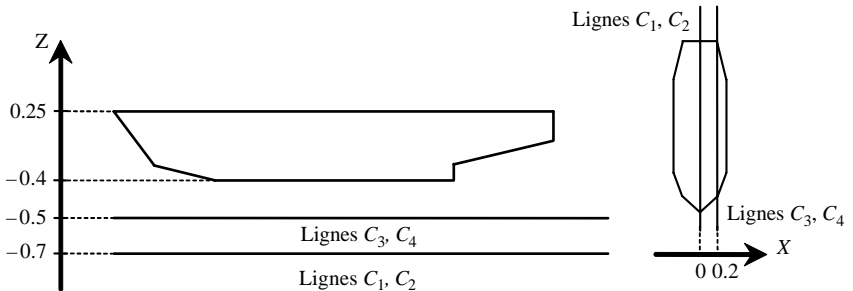
$$V_{\text{mes}}(P) = \frac{\mu_0 e}{4\pi} \sum_i^n \int_L \frac{M_i \cdot n_i}{r} dL_i \quad (7)$$

Both approaches have been implemented on a volume integral package called LOCAPI. This package allows computing shells' magnetization in earth's magnetic field. From a given magnetization state of a ship, magnetic gradient and potential are computed outside the ship. The validation has been made on four exploitation lines located at two distances below the mock-up (Figure 3).

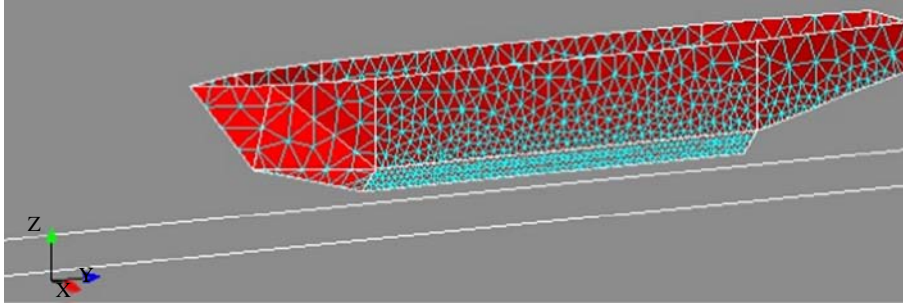
In order to generate, by a FEM tool, measurements which can be used as reference for the study, a good mesh quality must be defined essentially near the bottom of hull, near the measurement line (Figure 4). On the other hand, the used mesh by the moment method code will be coarser (Figure 7).

Then, the mock-up has been modeled in a FEM code [4] in order to verify the mesh quality, essentially in the bottom (Figure 4). Thus, the magnetic inductions on the first line from the two methods are compared (Figure 5). The two results are in a good agreement and the difference is lower than 5 per cent. The FEM magnetic field will be our reference.

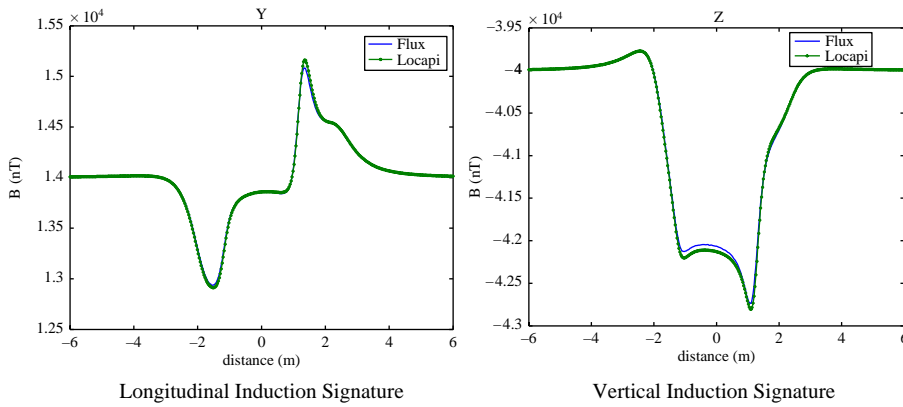
Figure 6 shows magnetic potential calculus on the line number one. Results obtained with an integral method (Locapi) show a good agreement with those obtained with a commercial FEM code [4].



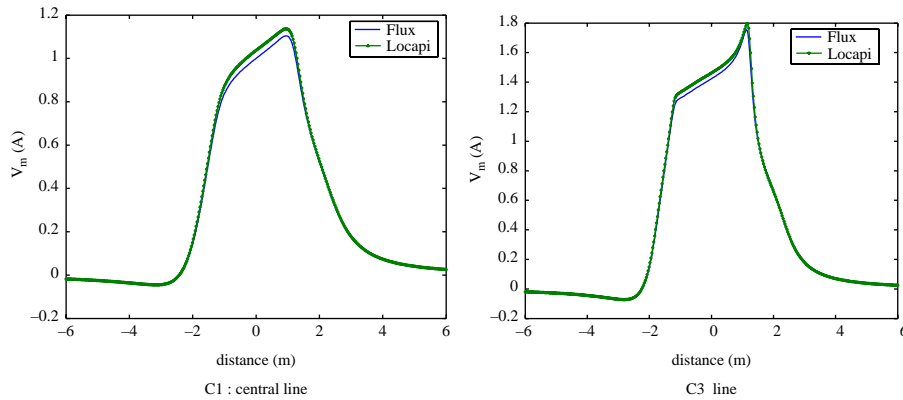
**Figure 3.**  
Lines outside the ship where the potential and the gradients are computed



**Figure 4.**  
Numerical mockup – FEM  
mesh



**Figure 5.**  
Induction computation  
with integral method  
(Locapi) and FEM



**Figure 6.**  
Comparison between  
magnetic potential  
obtained with integral  
method and FEM

### 3. Inverse problem formulation

Thanks to equation (5) and to  $m$  sensors located inside the hull, a linear system is carried out, with  $2n$  unknowns (two unknowns per element) and  $3m$  equations (three measurements per tri-axis sensors):

$$\mathbf{Ax} = \mathbf{b} \quad (8)$$

where:  $\mathbf{A}$ , links magnetization and radiated field;  $\mathbf{b}$  measurement matrix (usually induction);  $\mathbf{x}$ , magnetization vector of each element.

This matrix system defines the inverse problem, the relation between the magnetic sources and their effects.

This system is largely rank-deficient (less equations than unknowns) so it is ill-posed (Tikhonov and Arsénine, 1976). Thus, equations which take into account the physical behaviour of the shell are added (equation (9)) (Chadebec *et al.*, 2004):

$$[\mathbf{C} + \mathbf{I}\mathbf{C}]x = d \quad (9)$$

where:  $\mathbf{C}$ , describe the interaction between surfaces elements;  $\mathbf{I}$ , identity matrix;  $d$ , earth field values (induced field).

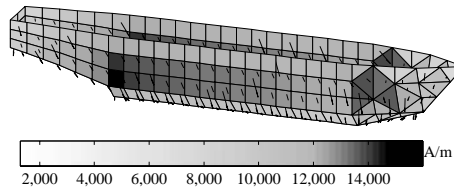
And a global inverse problem can be solved. This approach has been validated by real induction measurements:

$$\begin{bmatrix} \mathbf{A} & \mathbf{A} \\ \mathbf{C} + \mathbf{I} & \mathbf{C} \end{bmatrix} \begin{pmatrix} x_{\text{ind}} \\ x_{\text{per}} \end{pmatrix} = \begin{pmatrix} \mathbf{b} \\ d \end{pmatrix} \quad (10)$$

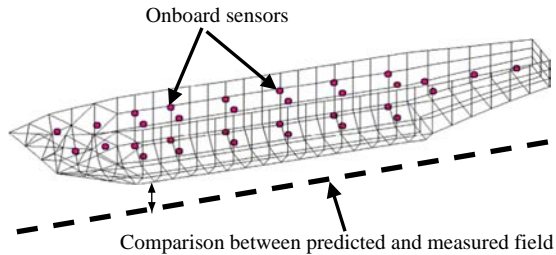
where:  $\mathbf{A}$ , links magnetization and radiated field;  $\mathbf{C}$ , describe the interaction between surfaces elements;  $\mathbf{I}$ , identity matrix;  $\mathbf{b}$ , measurement matrix (usually induction);  $d$ , earth field values (induced field).

We now test it, with magnetic potential measurements and scalar magnetic gradient measurements simulated numerically.

The mock-up is given a realistic magnetization (induced + remanent). The following mock-up magnetization model (Figure 7) gives us numerical measurements and a reference signature outside the ship (Figure 8). These virtual measurements could be magnetic potential measurements or magnetic gradient measurements.



**Figure 7.**  
Mock-up of the ship magnetization reference



**Figure 8.**  
Mock-up of the ship magnetization reference

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The approach based on the moment method needs 271 surface elements and 32 on board induction magnetic sensors.

Obviously, sensors' positions inside the hull play an important role in magnetization identification. In particular, distances between the hull and sensors appear to be a very important parameter.

Then, this bench allows generating:

- a magnetization state of the mock-up (induced and remanent);
- virtual measurements; and
- resolution and prediction of the magnetic anomaly everywhere inside and around the ship.

### 3.1 Magnetic gradient

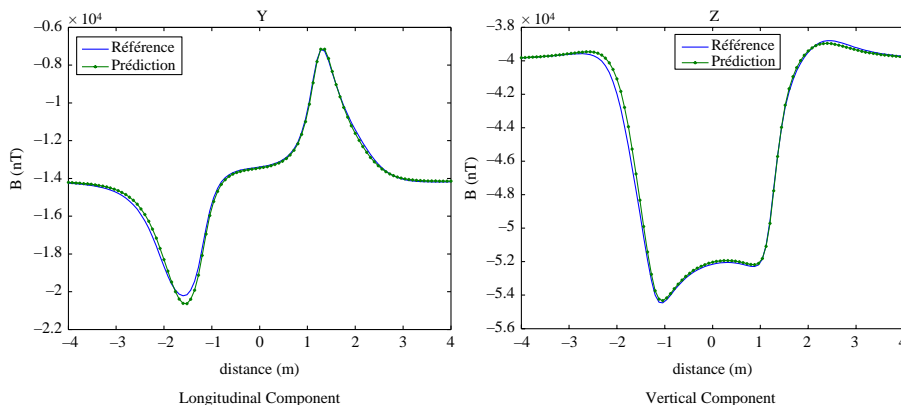
Generated measurements are now magnetic gradient measurement. These measurements are defined as equation (1) and validated by differential induction measurements. System obtained with equation (6) is solved. Let us notice that additional equations are added as in Chadebec *et al.* (2004).

As shown on Figure 9, the results obtained for the resolution of the inverse problem from gradients measurements are in a good agreement with the reference. In this configuration, 83 simulated gradient sensors are used inside the hull. An experimental validation has been carried out in Guerin *et al.* (2005).

The magnetic gradient measurements offer new possibilities for the resolution of this inverse problem. In particular, one of its main advantages, in comparison with induction measurements, is to avoid that internal ferromagnetic masses (which are not taken into account in the model) decrease the quality of the inversion process ( $1/r^3$  decrease law for gradient against  $1/r^2$  decrease law for induction).

### 3.2 Magnetic scalar potential

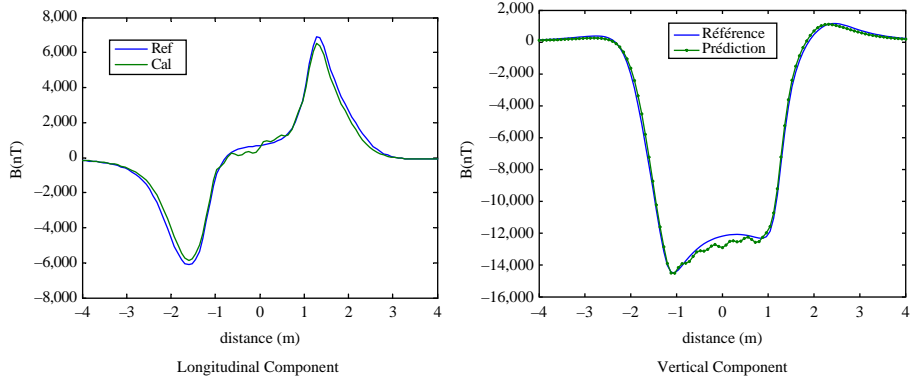
As shown on Figure 10, it is possible to solve inverse problem from potential measurements. Here, only 20 potential sensors are used in this configuration. The predicted signature presents a good agreement with the reference. Results are



**Figure 9.**  
Signature predictions  
obtained from magnetic  
gradient measurements  
after resolution of the  
inverse problem

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**Figure 10.** Signature predictions obtained from magnetic potential measurements after resolution of the inverse problem



equivalent to those obtained with gradient but with less sensors. The main advantage of potential measurements is to provide a global magnetization state for the hull, by smoothing local anomaly (see decrease law).

#### 4. Conclusion

Previously only induction measurements were used to solve magnetization identification problem (results of an inverse problem). We introduce the possibility to use other kinds of values like magnetic gradient measurements or magnetic potentials.

This approach has been made virtually with simulated measurements. It has been validated experimentally only for gradient measurements. Usually, magnetic gradient measurements are carried out with several induction measurements (fluxgate) closed to each other.

The potential measurements seem to be an attractive approach. In particular, only few measurements are needed. Unfortunately, this kind of measurements is difficult to manage (need of an appropriate potential sensor) and has not been tested yet on a real mock-up.

The use of these two kinds of measurements combined with the induction measurements should be an interesting approach to extract local or global information and to improve the quality of the inversion process.

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