Magnetic gradient and magnetic potential for surface devices in magnetostatic applied to the resolution of inverse problem for closed-loop degaussing computation

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Magnetic Gradient & Magnetic Potential for Surface Devices in Magnetostatic applied to the resolution of inverse problem for closed-loop degaussing computation

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Abstract **This paper presents the use of magnetic gradient, and magnetic potential measurements in the specific case of magnetisation identification for a thin sheet. A brief description of these notions and the method to calculate them are presented and validated. These two kinds of measurements are tested for a numerical identification case. Advantages of using induction, magnetic gradient or magnetic potential measurements are then discussed.**

Keywords : Magnetic Gradient, Magnetic Potential, Inverse Problem, inversion criteria, Magnetic Signature.

I. 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. 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 magnetisation.

In our approach we use induction measurements inside the hull. From these measurements, by solving the inverse problem, we obtain the magnetization distribution on the hull. Then, it is possible to predict the magnetic field outside the hull (signature …) and to reduce it by adjusting currents in degaussing loops [1].

However, induction measurements are not the only ones which can be provided. This paper proposes to solve the inverse problem with two new kinds of measurements: magnetic gradient and magnetic potential. The work presented is a numerical study. Both kinds of measurements inversions are tested and their reliability to predict the field outside the ship is presented.

II. DIRECT PROBLEM FORMULATION

Considering the magnetic induction vector B(P), we can define the magnetic gradient as (1)

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

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

$$Tr(G(P))=0 \quad and \quad G(P)^T=G(P) \quad (2)$$

With: Tr(A) the trace of the A matrix.

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

$$G(M)=\begin{bmatrix} \frac{\partial \vec{B}}{\partial x} & \frac{\partial \vec{B}}{\partial y} & \frac{\partial \vec{B}}{\partial z} \end{bmatrix} \quad (3)$$

Let us consider the surface S, mesh 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. Each element S_i has a uniform magnetisation $\mathbf{M_i}$, the induction created by S on a sensor placed at a point P located in the air region is:

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

with r is the distance between the sensor and the integration point.

This expression is an integral one and directly links the hull's magnetisation to the induction measurements. This expression is then easy to inverse.

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

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

Same expressions can be provided for the other components.

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

$$V_{mes}(P)=\frac{\mu_0 e}{4\pi}\sum_i^n \int_L \frac{M_i.n_i}{r} dL_i \quad (6)$$

Both approaches have been implemented on a volume integral package called LOCAPI. This package allows to

compute shells magnetisation in earth's magnetic field. From a given magnetisation 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 (see Fig 1.).

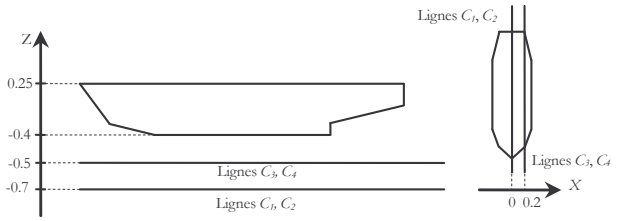
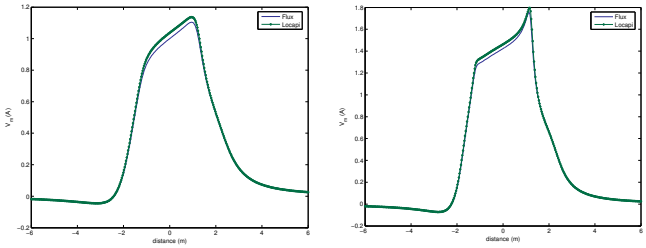


Fig 1: Lines outside the ship where the potential and the gradients are computed.

Results obtained show a good agreement with those obtained with a commercial FEM code (see Fig 2. for the magnetic potential).



C_1 : central line C_3 line

Fig 2: Comparison between magnetic potential obtained with integral method and FEM.

III. INVERSE PROBLEM FORMULATION

Thanks to equations (5) and to m sensors located inside the hull configuration, a linear system is carried out, with 2n unknowns (2 unknowns per element) and 3m equations (3 measurements per tri-axis sensors). This system is largely rank-deficient (less equations than unknowns) so it is ill-posed. Thus equations which take into account the physical behaviour of the shell are added [2]. This approach has been validated by real measurements. We now test it with potential and gradient measurements simulated numerically.

The following mock-up magnetization model (see Fig.3.) gives us numerical measurements and a reference signature outside the ship.

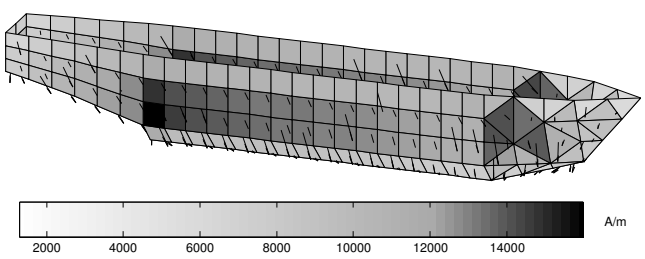


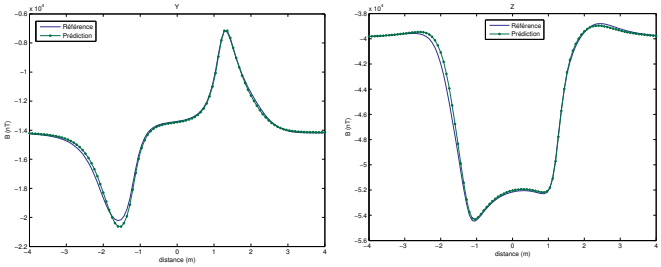
Fig 3: Mock-up of the ship magnetization reference

We have to place correctly sensors in order to obtain a good agreement with the signature comparisons. Sensors are placed near the hull and the distance between sensors and it appears to be a very important parameter.

A. *Magnetic Gradient*

System obtained with equation (5) is solved. Let's notice that additional equations are added like in [2].

As shown on Fig 4 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. An experimental validation has being carried out in [3].



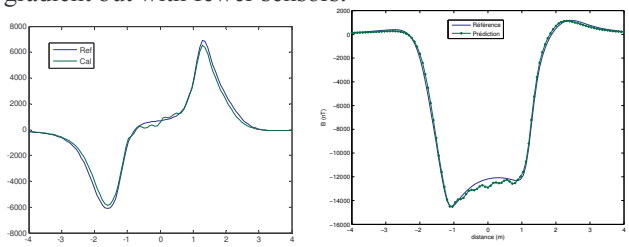
Longitudinal Component Vertical Component

Fig 4: Signature Predictions obtained from magnetic gradient measurements after resolution of the inverse problem.

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 taking 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).

B. *Magnetic Scalar Potential*

As shown on Fig 5 it is possible to solve inverse problem from potential measurements. Here only 20 potential sensors are used in this configuration. The signature prediction presents a good adequation with the reference. Results are equivalent to those obtained with gradient but with fewer sensors.



Longitudinal Component *Vertical Component*

Fig 5: Signature Predictions obtained from magnetic potential measurements after resolution of the inverse problem.

The main advantage of potential measurements is to provide a global magnetisation state for the hull, by smoothing local anomaly (see decrease law).

IV. CONCLUSION

Previously only induction measurements were used to solve magnetisation identification problem. We introduce the possibility to use other kinds of measurement like magnetic gradient or magnetic potential. This virtual approach has been validated experimentally for gradient measurement. 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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