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Robustness of a Magnetostatic Inverse Problem Resolution

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Abstract:

This paper presents the preliminary step of a study on the sensitivity of an inverse problem algorithm used to determine the magnetization of a ship.

The robustness is evaluated with respect to different measurement errors, as misalignment, noise on sensors and estimation of local field ….

Only simulated magnetisations to obtain numerical data are presented in this study

Key words: algorithm robustness, inverse problem, magnetostatic low-field, inversion criteria, simulated magnetic measurement.

I. INTRODUCTION

The Ships Magnetism Laboratory works on the magnetic protection of ships and equipments for the navy.

This paper focuses on the steady-state magnetic signatures created by vessels with ferromagnetic hull. This magnetic anomaly depends upon the hull's magnetization. It's a combination of an induced magnetization and a remanent one. The first is created by Earth magnetic field. It is due to the reaction of the material when it is placed in an inductor field $\mathbf{H_0}$ (i.e. earth magnetic field). The induced magnetization calculus is now well-known and easy to compute [1][2]. The remanent magnetization depends on the magnetic history of the material (combination of mechanical and thermal constraints, magnetostriction, etc…). As, we have not any knowledge about this history, magnetic measurements are necessary to evaluate the total magnetization; in our application sensors are placed onboard the ship.

II. CONTEXTE

a. *Inverse problem*

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 …) [3].

This inverse problem can be defined as (1):

$$A(x) = b \tag{1}$$

with:

A: matrix of the forward problem
x: sources to identify.
b: measurements of the magnetic field.

To solve inverse problem, it consists to find x from A and b (known).

Typically, an inverse problem is ill-posed (less equations than unknowns) and the solution is not unique. The founded x must fit the measurements and must be in good agreements with the physic.

b. *Global Magnetization*

Moreover, to solve correctly this problem we must take into account the global magnetization. This magnetization is composed of the induced magnetization and remanent one (2).

$$\mathbf{M} = \mathbf{M}_{\mathbf{ind}} + \mathbf{M}_{\mathbf{per}} \tag{2}$$

with:

M: global magnetization
$\mathbf{M_{ind}}$: induced magnetization
$\mathbf{M_{per}}$: remanent magnetization

c. *Global System to solve*

The combination of (1) and (2) give us the linear equation (3). The solution returned by these resolutions is the distribution which fits the measurements and moreover which takes into account the behaviour of the material.

$$\begin{bmatrix} C + Id & C \\ A & A \end{bmatrix} \begin{bmatrix} x^{ind} \\ x^{per} \end{bmatrix} = \begin{bmatrix} d \\ b \end{bmatrix} \tag{3}$$

with:

C: geometry matrix (linear integral)
A: linear integral
I_d: identity matrix
d: inductor field Ho
b: measurements
x^{ind} or x^{rem}: induced or remanent magnetization to determine

III. STUDY DESCRIPTION

a. *Inverse problem*

The global objective of this study focuses on the definition of a method to optimize the number and the position of the sensors. The goal of this method is to improve the resolution of the inverse problem and to ensure the robustness of the algorithm with an optimal set of sensors [2]. To reach this objective, two successive steps are defined:

- The first is to find an optimal position for a given number of sensors.
- The second focus on the robustness of the optimal configuration selected.

Globally, if the robustness is not good enough, the sensor number is increased and the operation is restarted (Fig1). Thus by iteration, the minimum sensor number needed to obtain a powerful and robust system can be found. Here, just the robustness is presented.

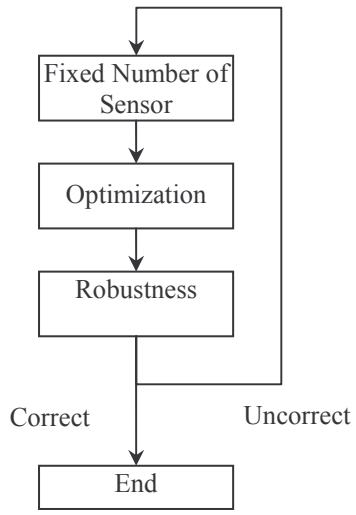

Fig1 : Diagram block of the study

Thus, to test the inversion quality criteria must be defined.

b. Inversion quality

How define a parameter which describes the quality of the inverse problem resolution. This parameter must describe if the measurement set of sensor is appropriate to our system (for optimization and robustness). For the robustness, with a fixed number of sensors the parameters must describe if the algorithm still converge and quantify the variation on the result. As the objective consists to predict signature of magnetized object (hull, vessel), the quality parameters are defined from the signature and not on magnetization.

Thus by computation, a reference signature is defined (*Ref*) and predicted anomaly (*Comp*) should be compared to reference one.

Two criteria have been chosen: a Fidelity Factor (*FF*) and the Normalized Quadratic Error (*NQE*).

$$FF = 100 \exp\left(-\frac{\|Comp - Ref\|}{\|Ref\|} - \frac{\|Comp - Ref\|^2}{\|Ref\|^2} \right) \quad (4)$$

$$NQE = \frac{\left\|(Comp - Ref)^2\right\|}{\|Ref\|^2} \quad (5)$$

with:

Comp: the computed anomaly.
Ref: the reference anomaly.
FF: criterion ranging between 0 and 100. It represents a percentage of a good agreement between two curves (signatures). Its main advantage consists on its quasi-linearity from 0 to 70% of error.
NQE: criterion which emphasizes local errors. A good factor is near in 0. This criterion is more sensitive than *FF*.

Each sensor configuration is then linked to a criterion (*FF* or *NQE*) which describes how signature is predicted and consequently how is the inversion quality.

c. Objective function definition

Associated to criteria, appropriate objective functions must be defined. These functions describe the signature behavior. In this case 5 objective functions are compared. These functions are based on the *FF* criterion. *NQE* is only used in this study to confirm results.

These criteria have been adapted for the optimization study. It minimizes an objective function.

$$\begin{aligned} f_1 &= 100 - FF_x & f_4 &= f_1 + f_2 + f_3 \\ f_2 &= 100 - FF_y & f_5 &= -\frac{f_1 . f_2 . f_3}{1000000} \\ f_3 &= 100 - FF_z \end{aligned} \quad (6)$$

with FF_x the *FF* criterion for *x* signature component.

Thus: *the* f_1, f_2 and f_3 factors correspond to only one signature component. It could seem to be useless to act only on one component because theoretically others should not evolve. Yet, according to material magnetization some signature components could be more sensitive.

f_4 and f_5 aim at optimizing all the components.

f_4 is a global objective function which gives the same importance to each signature component.

f_5 favors the weakest component and result is more homogeneous [2][3].

IV. ROBUSTNESS

As shown on Fig1, a global objective is required but the robustness problem is isolated and studied alone. Moreover the optimization technique has been described previously [2][3].

a. Configuration of the mock-up

Let us consider the mock up as shown in Fig2. By computation, this mock-up is affected to a remanent and induced magnetization.

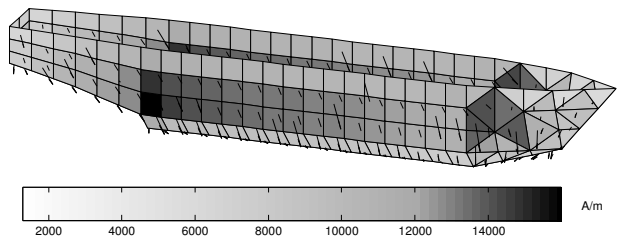

Fig2 : Mock-up of the ship magnetization reference

A longitudinal and vertical remanent magnetization is applied to the mock-up (0 nT; 23 000 nT; 41 000 nT)

previously. Then, an athwart ship induced magnetization is applied (23 000 nT; 0 nT; -41 000nT). Thus, virtual measurements can be generated to simulate sensor measurements inside the mock-up and the reference signature can be defined.

b. Sensor's distribution

Here a study with 35 sensors inside the hull is presented. The position of each sensor is fixed.

Sensors must be distributed in the hull. This sharing must take into account the mock-up geometry with specific areas and the magnetic behaviour of the hull. Thus, the volume in share in four dedicated areas (Fig3):

- The front of the mock-up with its particular form
- The bottom of the central part.
- The top of the central part
- The back with its breaking.

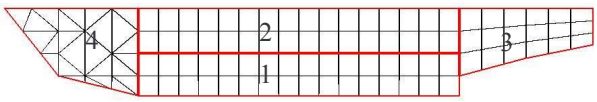

Fig3: four areas created inside the hull.

The number of sensor placed inside each area is defined in Table 1. The distribution of these sensors is shown in Fig4.

Table 1: Sensor distribution

	Area			
	1	2	3	4
Number of Sensor	17	8	6	4

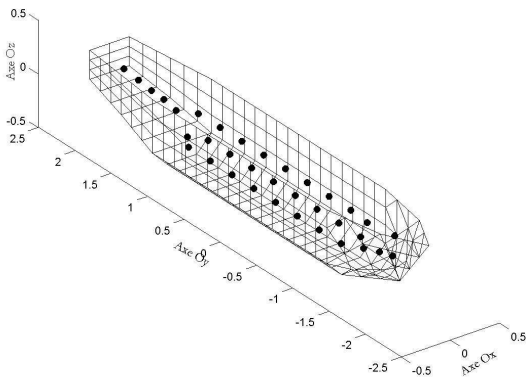

Fig4: 35 Sensors distribution in the ferromagnetic hull

c. Test parameters

As defined in (3), the inverse problem is based on the measurement. Thus, specific parameters concerning sensors and their potential induced errors have been identified. These errors concern noise, bad positioning misalignment and bad running.

Moreover, in the analysis of the equation (3) the knowing of the Earth field value appears as an important parameter.

In Table 2 these test parameters are defined. For each of them we have specified a variation range or a specific configuration.

Table 2: Robustness Tests Parameters

Robustness Tests	**Test Parameters**		**Comments**
Noise on all sensors	From -200 to +200 nT		Random error included between theses 2 values
Approximate Position of the sensors	According to Ox	Min: -0.001 m Max: +0.001 m	Random errors included between the two values corresponding to each axis
	According to Oy	Min: -0.002 m Max: +0.002 m	
	According to Oz	Min: -0.001 m Max: +0.001 m	
Sensor's Misalignment	Around Ox	Min: -0.1 ° Max: +0.1 °	Random errors included between the two values corresponding to each axis
	Around Oy	Min: -0.1 ° Max: +0.1 °	
	Around Oz	Min: -1 ° Max: +1 °	
Sensor(s) Out of Service	Area n°1	1 sensor HS	For each area random specification of the sensors
	Area n°2	0 sensor HS	
	Area n°3	1 sensor HS	
	Area n°4	1 sensor HS	
Error on the terrestrial field value	According to Ox	10 %	For each axes, possibility to include a relative random error or an absolute error
	According to Oy	200 nT	
	According to Oz	10 %	

d. Reference Configuration

According to the mock-up magnetization as mentioned previously on a) the ideal signature is established (reference signature).

Using the sensor distribution as specified on b), virtual measurements on each sensor are generated. Then the inverse problem is solved to obtain the hull magnetization. From this magnetization distribution, the signature is computed (*Comp*).

This reference configuration is specified as ideal configuration, with perfect measurements without error or problem. Previous criteria values are calculated and defined as Reference Criteria - Table 3.

Table 3: Results of the Reference Test

Result of the Inversion Criteria Value : FF_norm		
According to Ox	According to Oy	According to Oz
99.919 %	90.578 %	99.11 %

e. Test Results

A protocol to generate theses different configurations as previously defined in Table 2 has been implemented around LOCAPI Software [4]. Each test is evaluated independently.

As shown in Table 4, it is interesting to observe the variations of the quality criteria.

Table 4 : Robustness Test Results

Robustness Tests	Result of the Inversion Criteria Value : FdF_norm		
	According to Ox	According to Oy	According to Oz
Noise on all sensors	99.910 %	90.521 %	99.096 %
Approximate Position of the	99.918 %	90.606 %	99.116 %
Sensor's Misalignment	99.88 %	90.953 %	99.163 %
Error on the terrestrial field	91.410 %	78.870 %	89.073 %
Sensor Out of Service	99.919 %	84.781 %	98.571 %

The range variation of noise is set to 200 nT. This value is four times larger than for our sensors. If 35 sensors are used, it seems that the noise has no really influence on the algorithm.

The error on the position is fixed to 1mm (large value) and on the alignment to 0.1°. In the same way results seem that it is not really important to define exactly the position or the reference alignment of the 3 axis sensors.

According to the Earth magnetic field value, these results Table 4 confirm the necessity to know it correctly. It's interesting to observe that an error around 10% of the earth field value give a result affected in the same ratio. This result seems natural, i.e. the solution of the equation (3) is oriented by the value of the Earth field.

Moreover, this result on an inverse problem is interesting to. Typically this inverse problem is ill-posed and its matrix conditioning is not good. A result limited on the same proportion of the information source variation can be correct. This result seems that the algorithm still converges in spite of errors.

V. CONCLUSIONS

The Locapi algorithm software has been tested and validated previously with an experimental validation. But it has been made in a magnetic control environment: the LMMCF – Experimental Magnetic Laboratory of the LMN.

The interest of this study lies to know or identify the limits of the inverse problem resolution for a future application.

To test the robustness, the sensor number has been started from 20 and increased to 35. The different robustness tests take into account the magnetic environment and uncontrolled parameter concerning sensors. This study shows us that we have to define a dedicated spatial domain for each sensor.

Results confirm the importance of the local earth field measurement on the inversion quality.

Moreover it seems that the majority of the other errors have little influence on the inversion quality. According to these results we have to take into account the number of sensor used and the simple geometry of the mock-up. It will be interesting to confirm this study results with a more complex mock-up (with desk …) and an experiment validation.

During this study, we have defined the bases of a method to test the robustness of an inverse problem algorithm. This method gives us relative correct results. It could be interesting to improve this robustness approach by association of the optimization method.

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